

# FLUID INJECTION TRIGGERING OF THE 2011 EARTHQUAKE SEQUENCE IN OKLAHOMA

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Photos by K. Keranen, The Oklahoman (<http://newsok.com/record-5.6-magnitude-earthquake-shakes-oklahoma/article/3620706>), and B. Sherrod

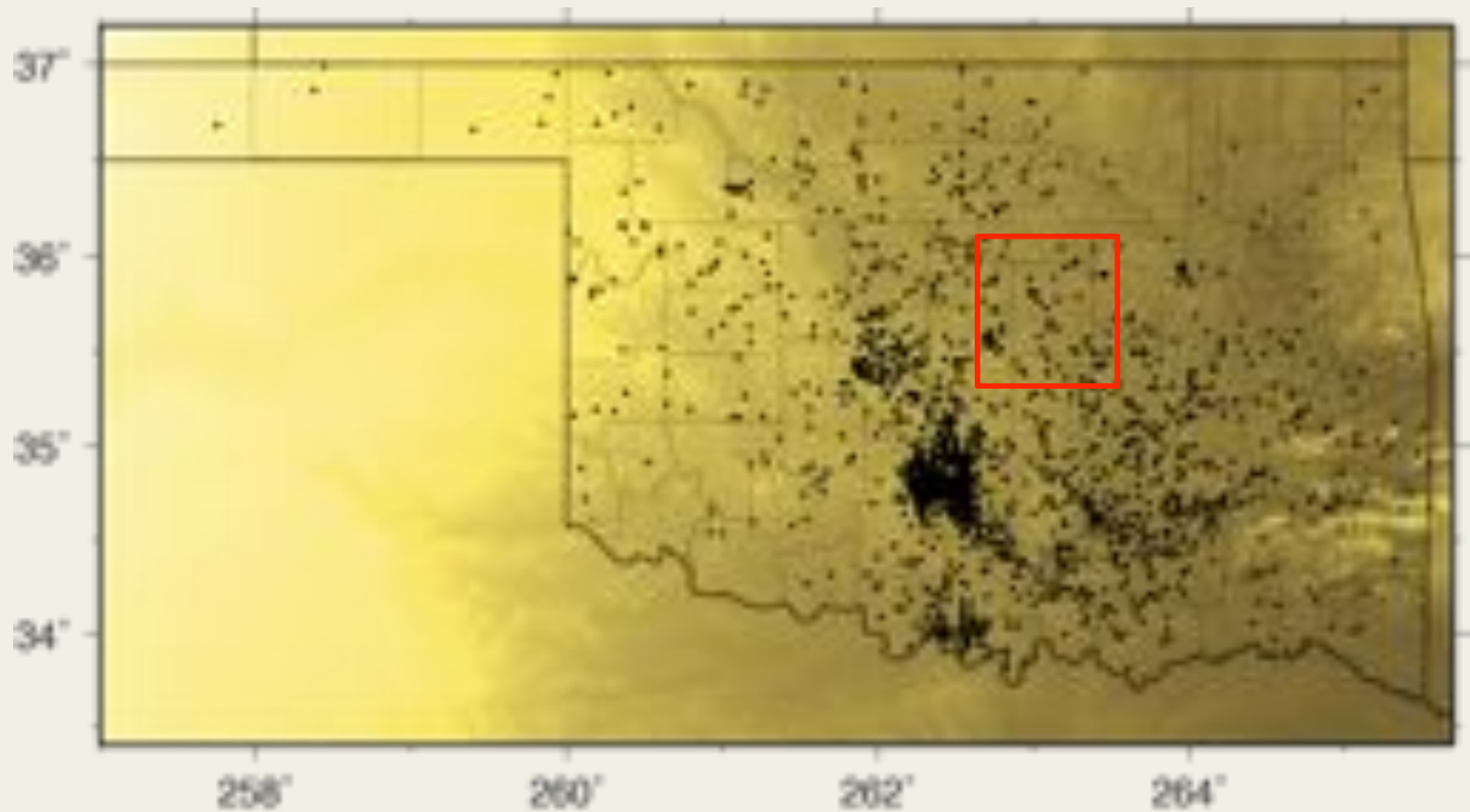


# Mw 5.7 Nov. 6, 2011



Photos by K. Keranen, The Oklahoman (<http://newsok.com/record-5.6-magnitude-earthquake-shakes-oklahoma/article/3620706>), and B. Sherrod

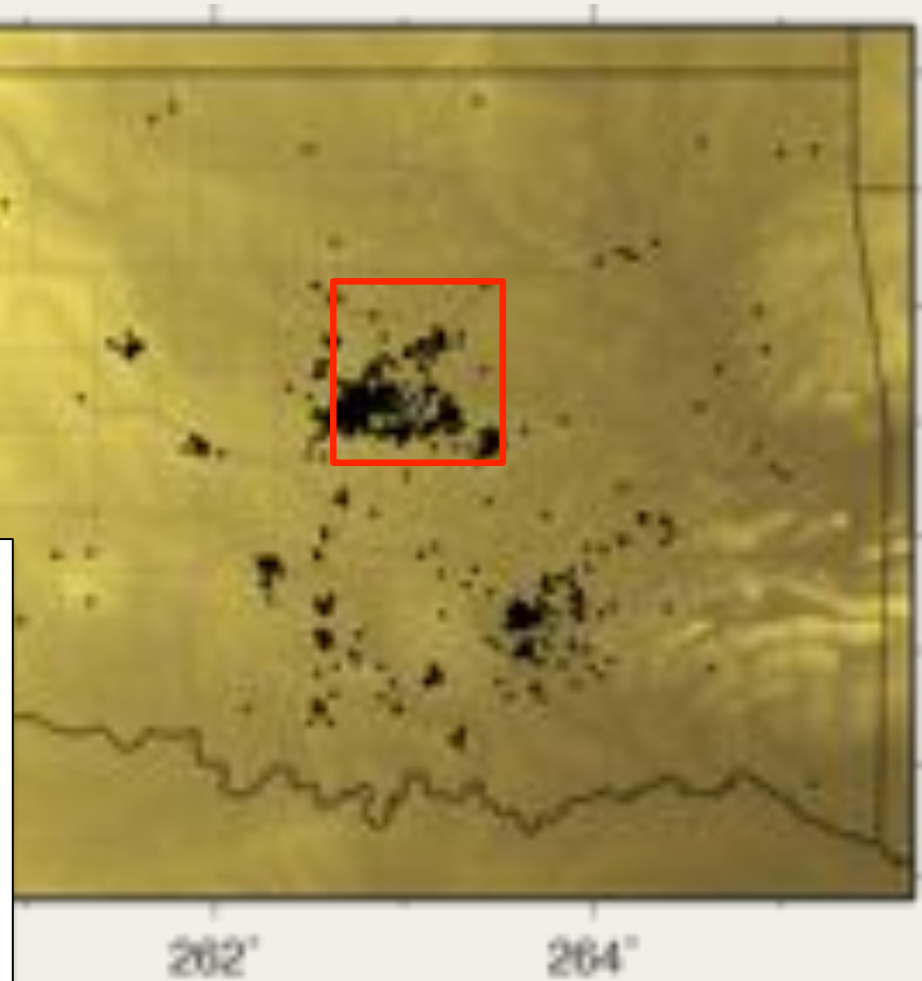
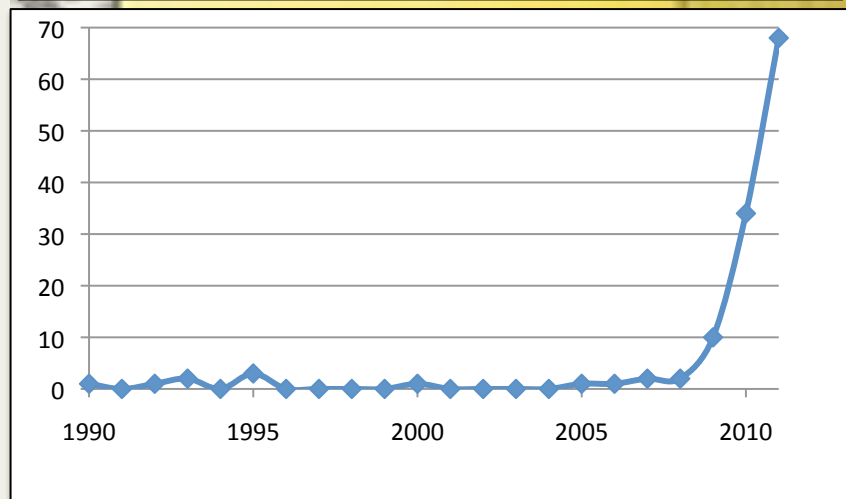
# Earthquakes in Oklahoma 1977-2009



OGS catalog locations

# Earthquakes in Oklahoma 2010-2011

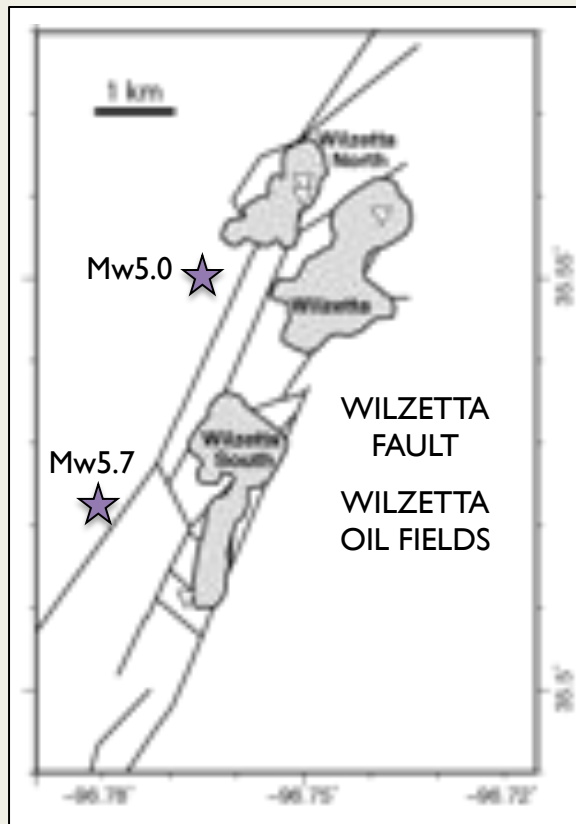
A sharp increase in M3+ earthquakes in Oklahoma since 2009



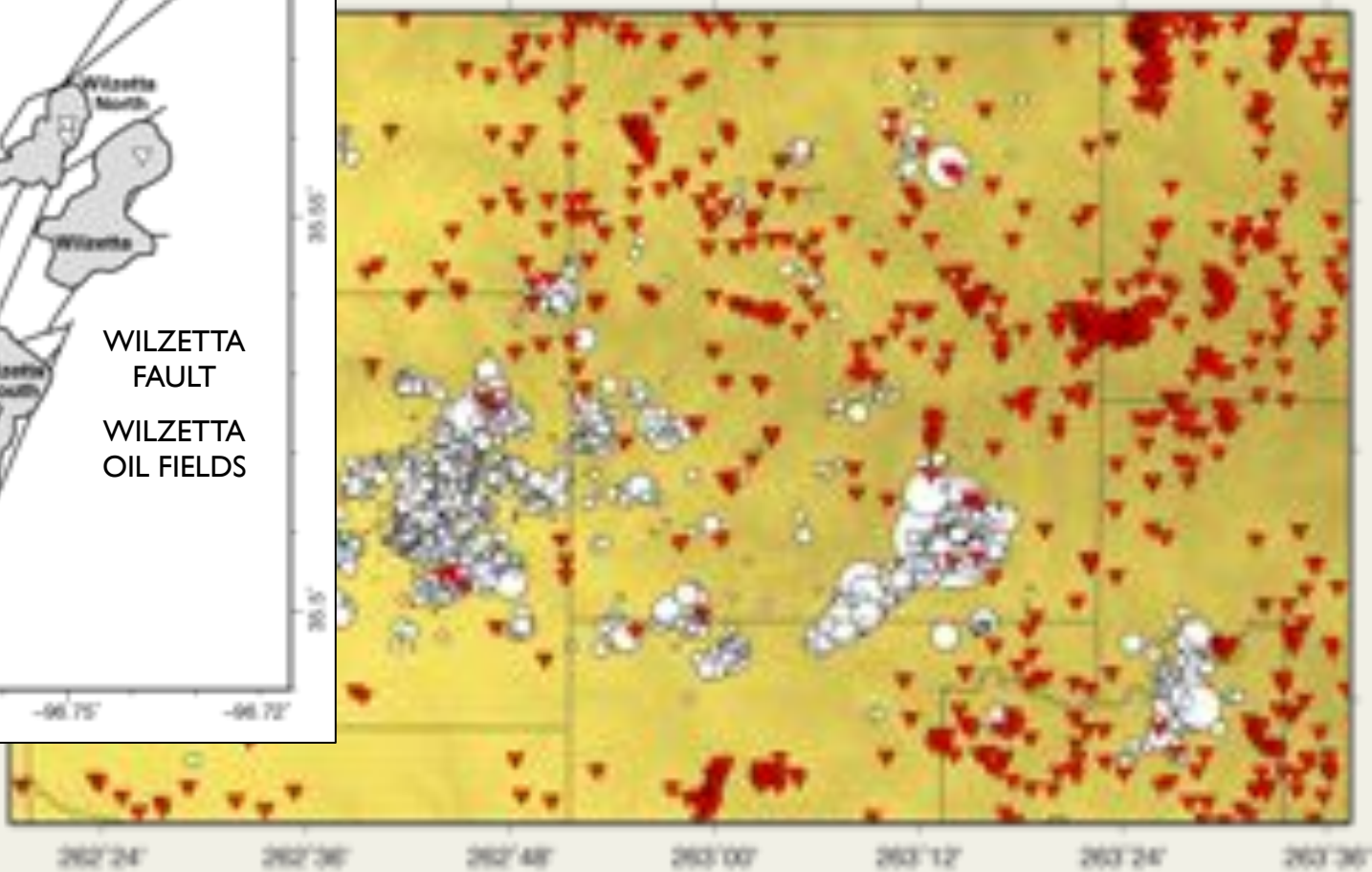
OGS catalog locations



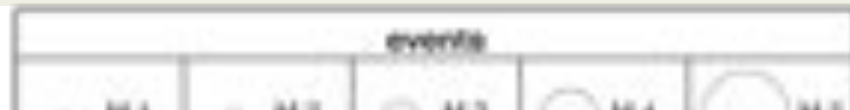
# Thousands of active wastewater injection wells



Faults merged  
from Way, 1983  
and Joseph, 1987;  
Field outlines from  
Way, 1983

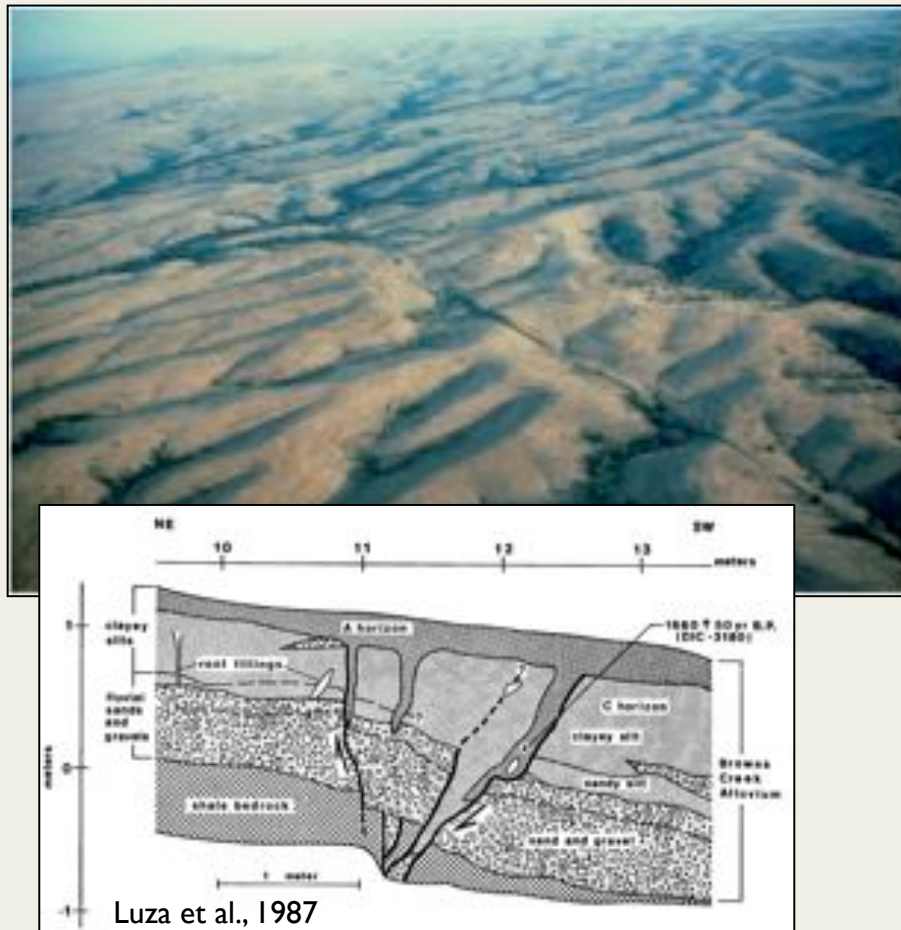


OCC well database; OGS catalog locations



# Large earthquakes have historically occurred within Oklahoma

Meers Fault – ~M7.0 1200 ybp



1952 M5.5 El Reno earthquake

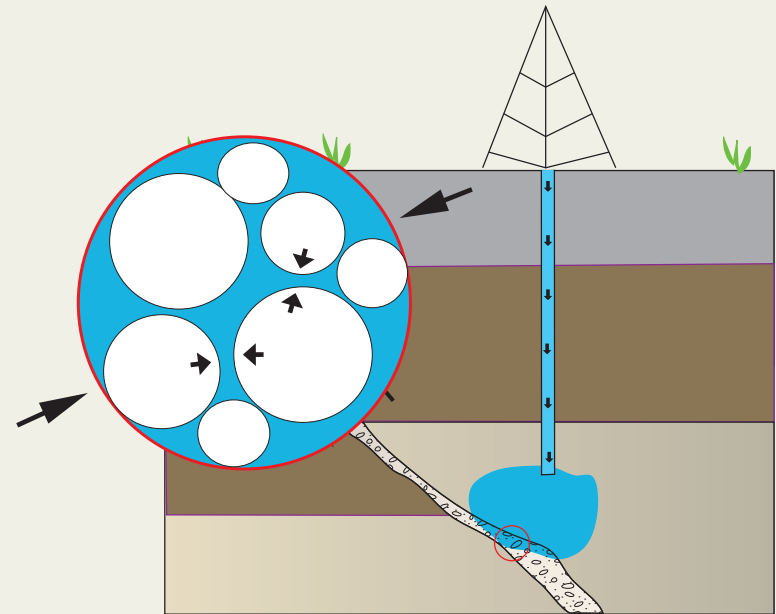


Stover and Coffman, 1993

# Was this earthquake sequence tectonic or induced?

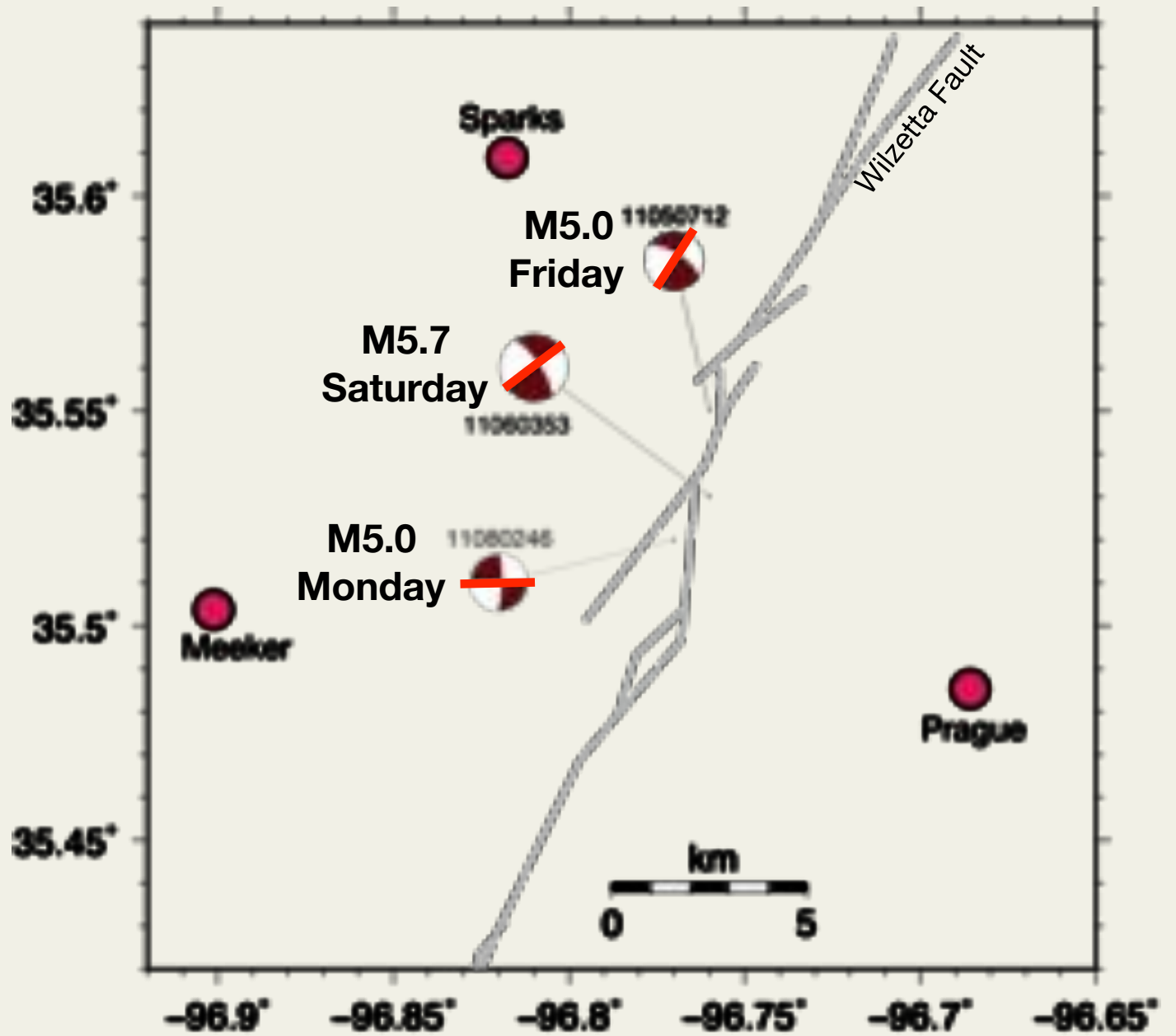


**or**



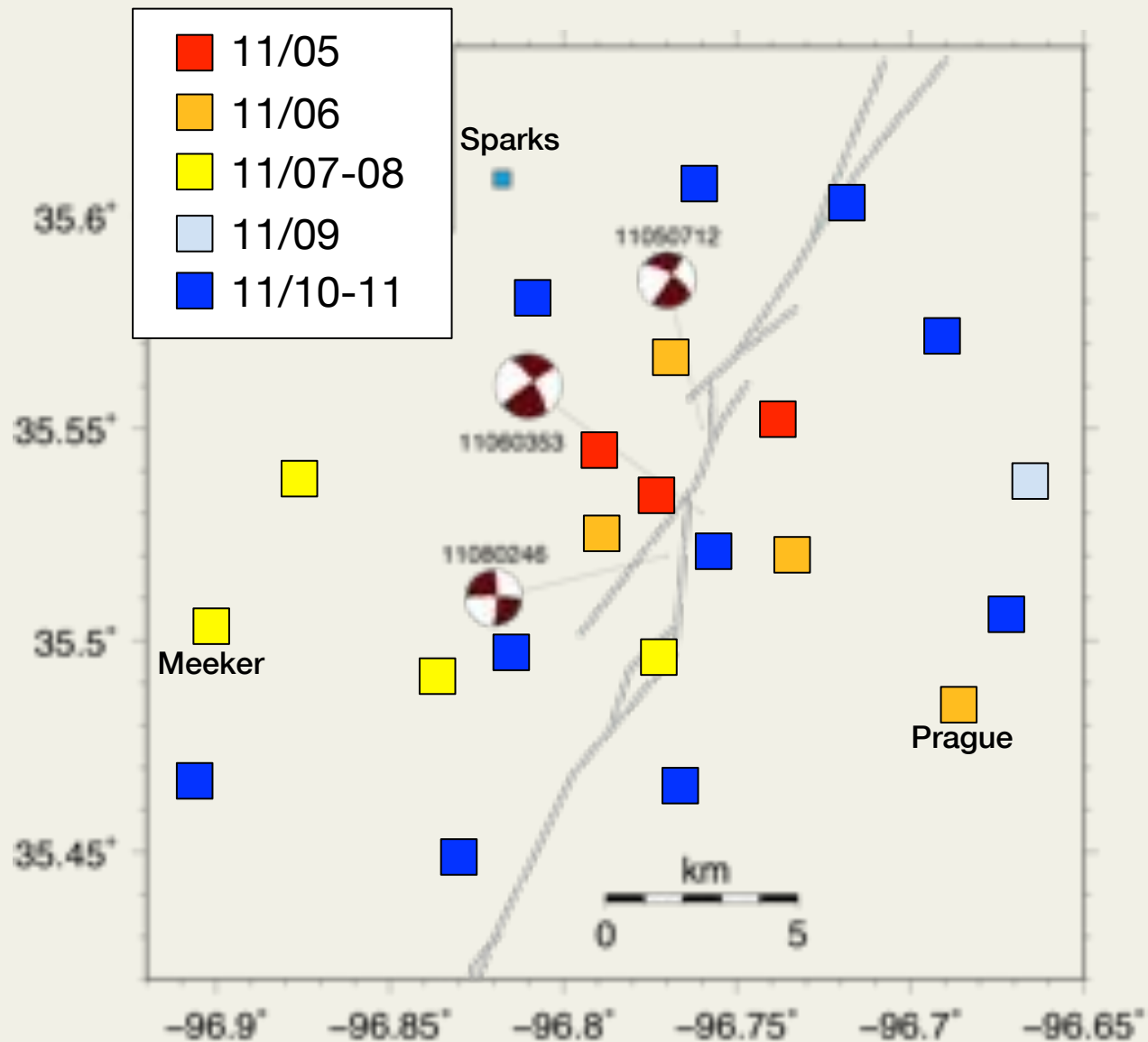
From H. Savage

# The earthquake sequence

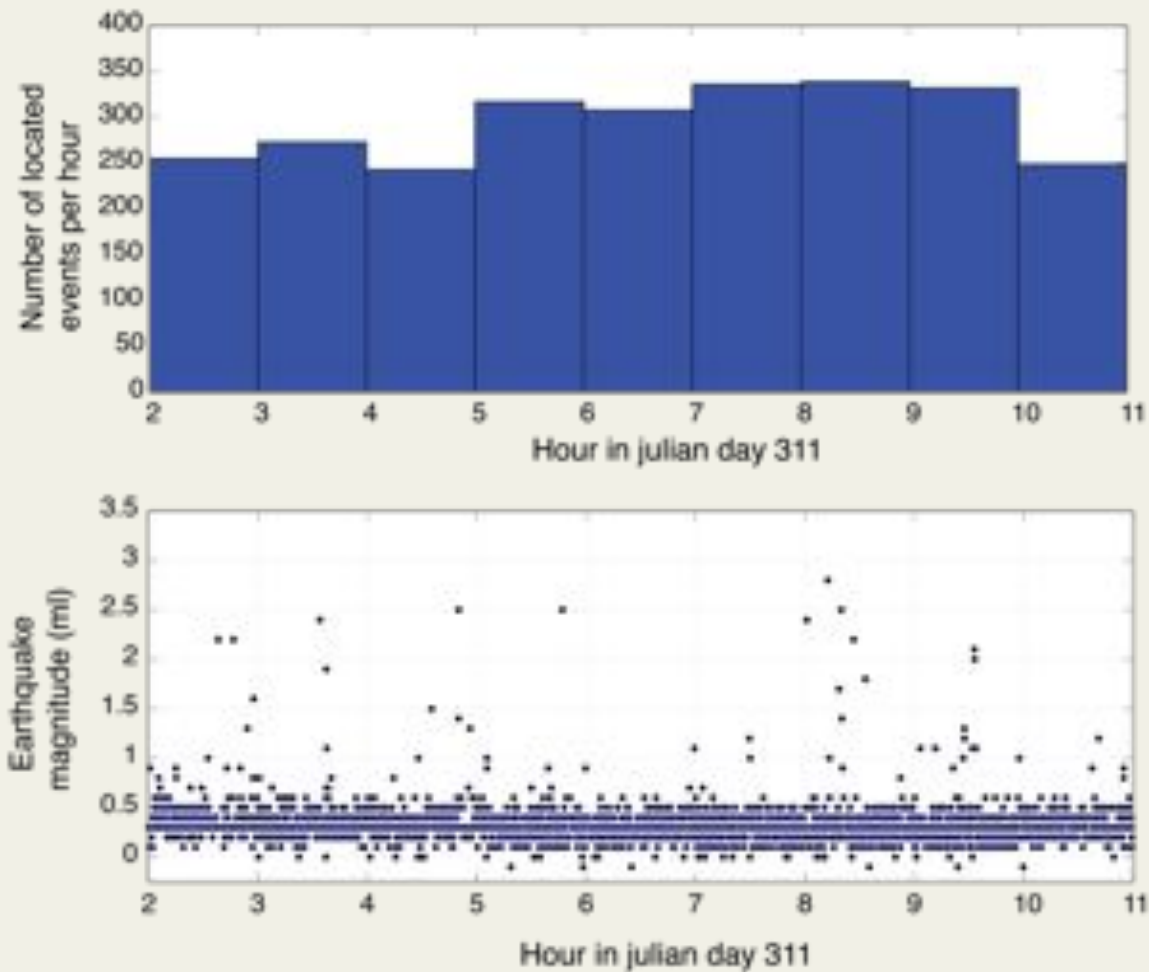




# Rapidly deployed array: OU, RAMP, USGS, NetQuakes

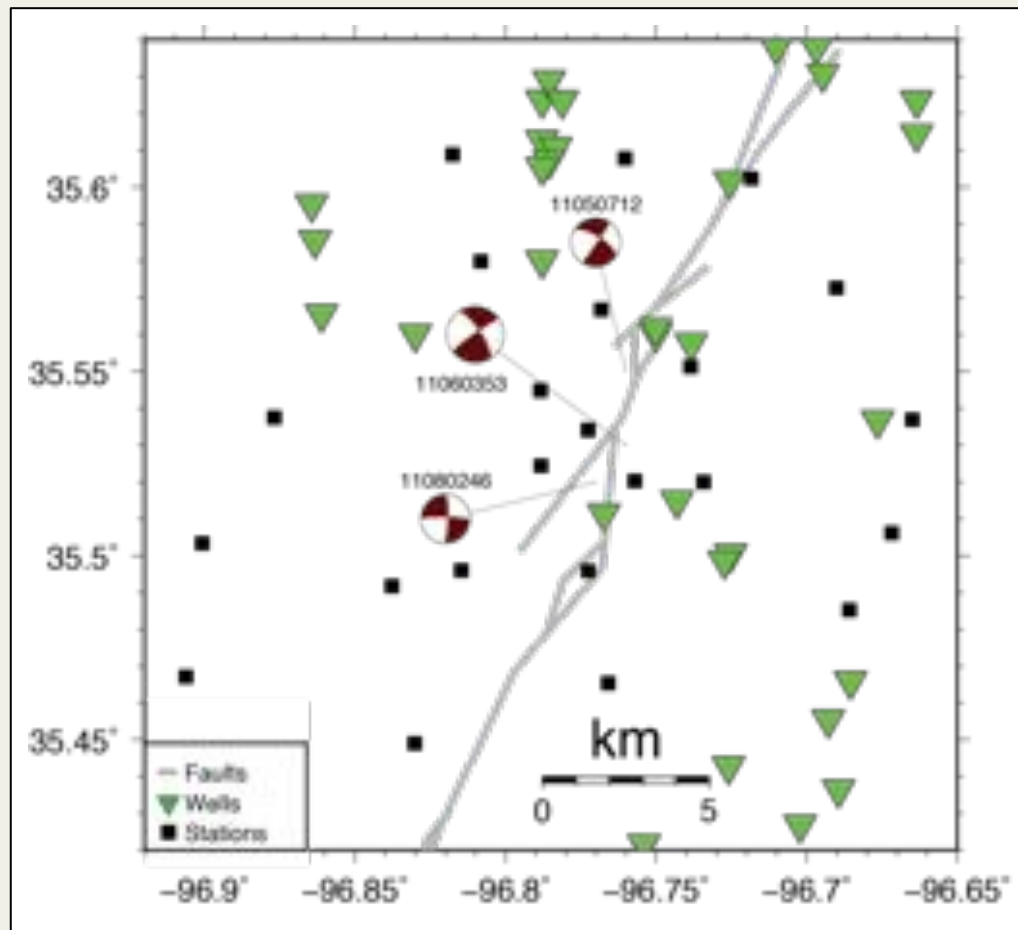


# A prolific sequence of earthquakes

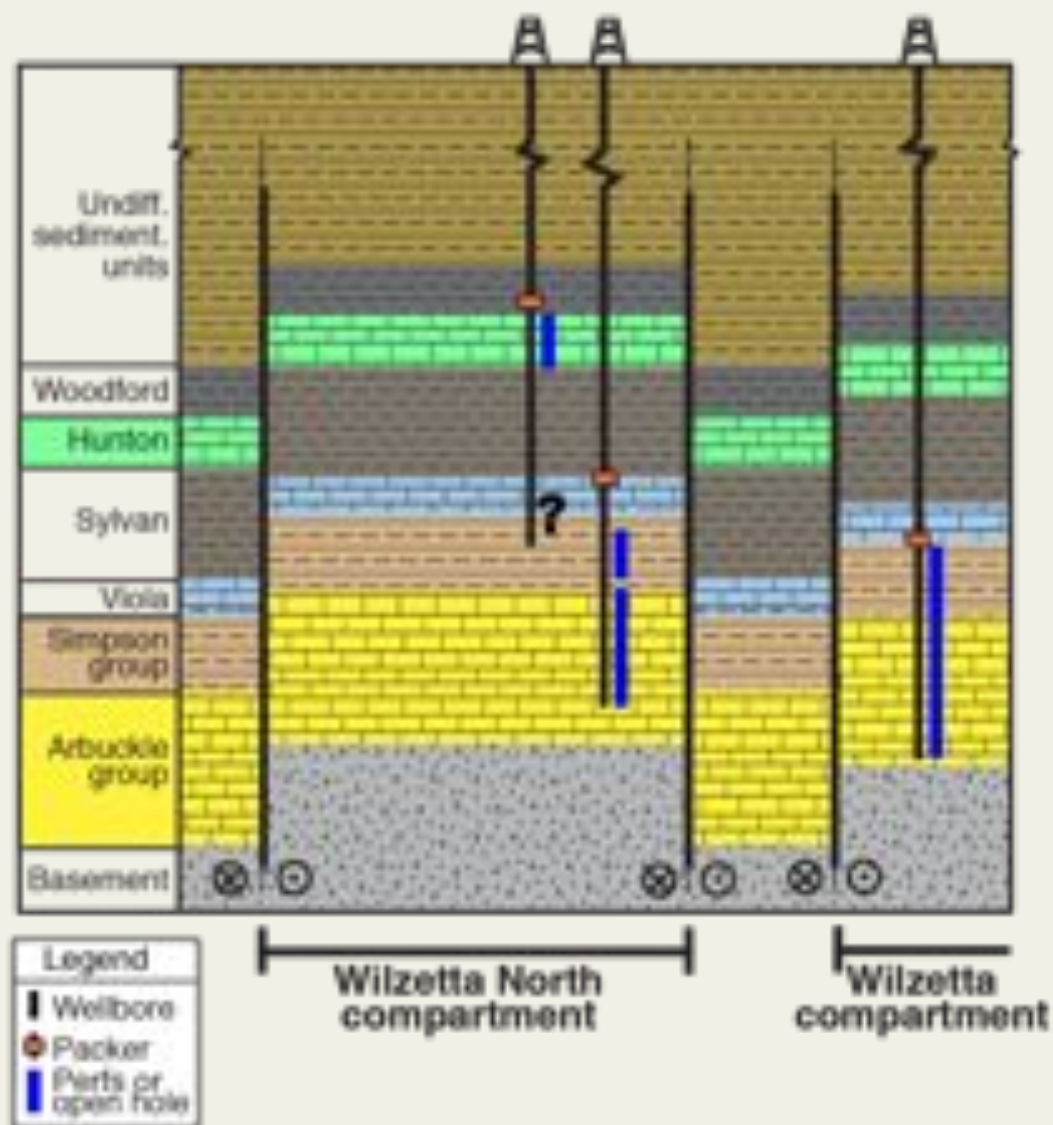


Average of nearly 300 located earthquakes/hour

Shallow seismic velocity:  
Subsurface stratigraphy is constrained by hundreds of well penetrations (figure shows a small subset)



# Sedimentary units and injection within the Wilzetta field

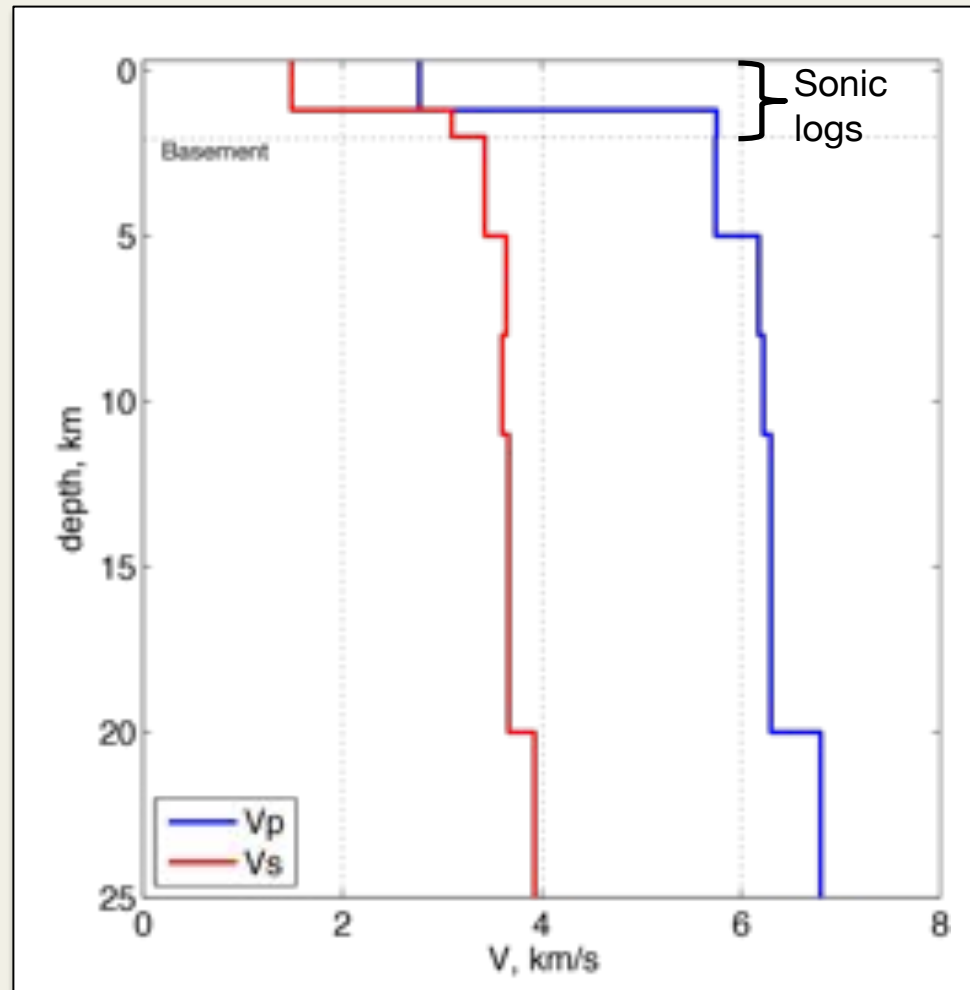


Strat column modified from  
Bauernfeind, 1982



# 1D velocity inversion:

Constrained by sonic logs ( $V_p$  only) and known formation boundaries



$V_p$ ,  $V_s$ , and  $V_p/V_s$  ratio from inversion fall inside bounds from lab measurements on Oklahoma carbonates

Timeline

OU, RAMP, USGS  
stations deployed

M4.7

11082011

4 OU stations deployed

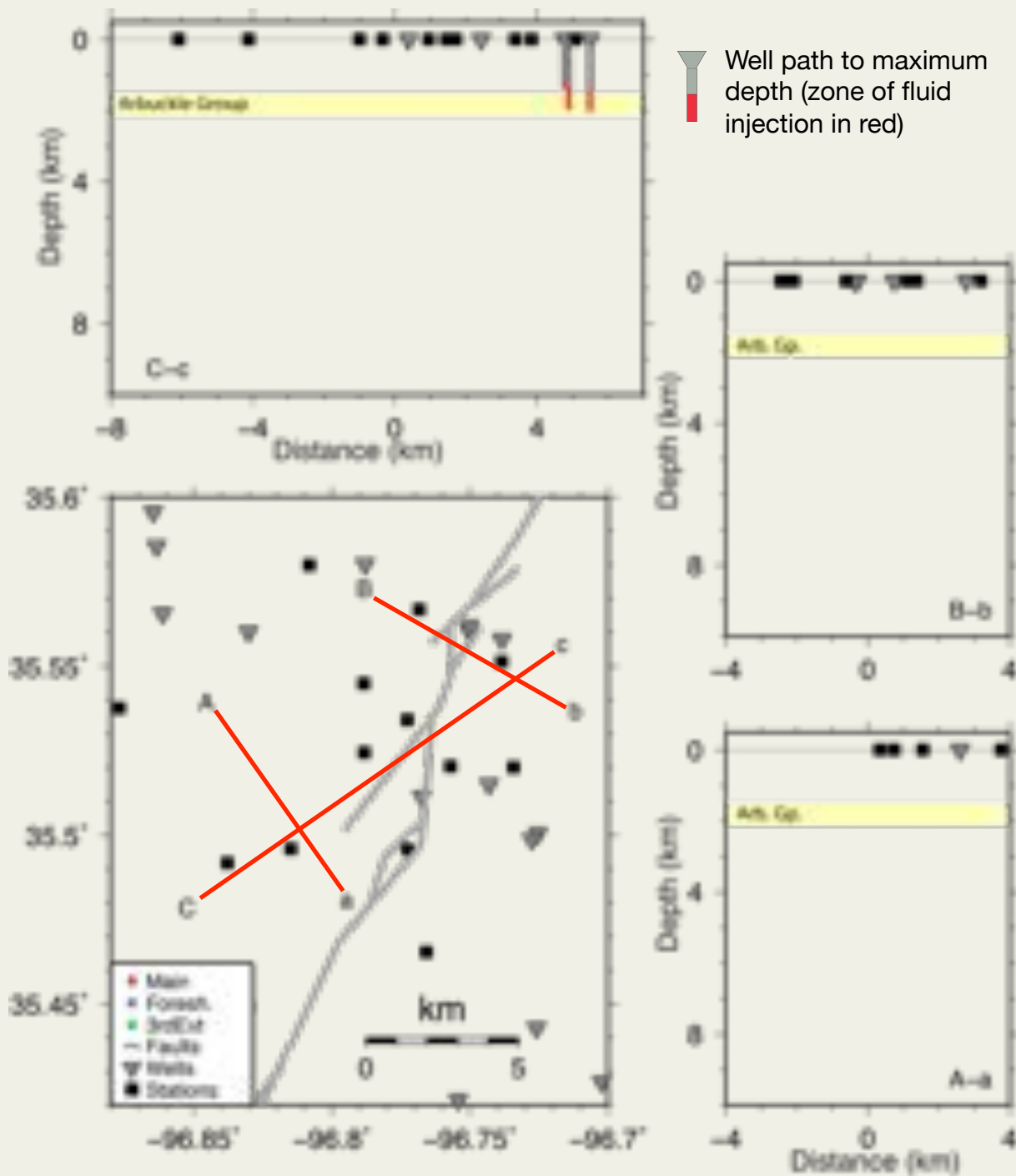
M5.6

11062011

3 OU stations  
deployed

M4.7

11052011



Template

Timeline

OU, RAMP, USGS  
stations deployed

M4.7

11082011

4 OU stations deployed

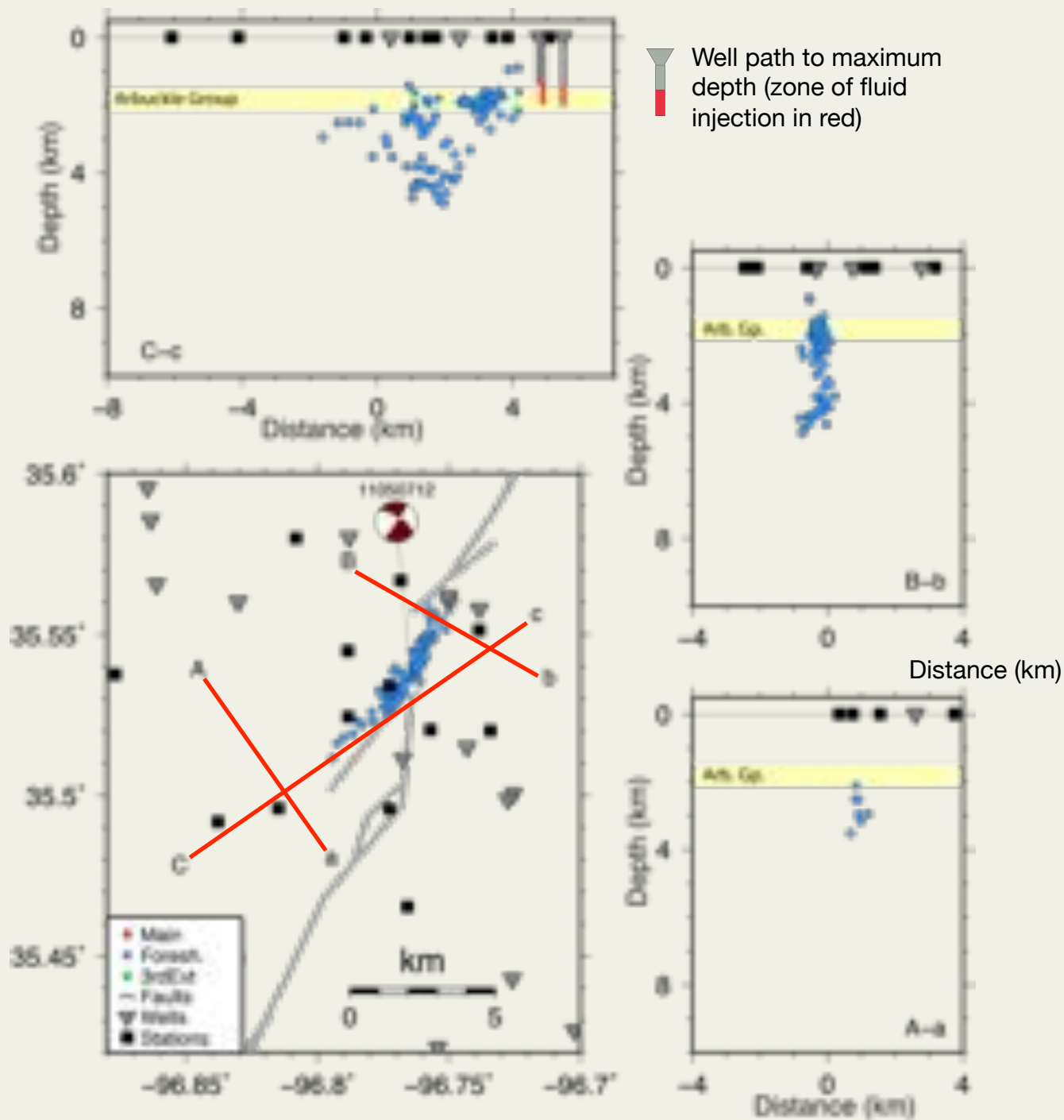
M5.6

11062011

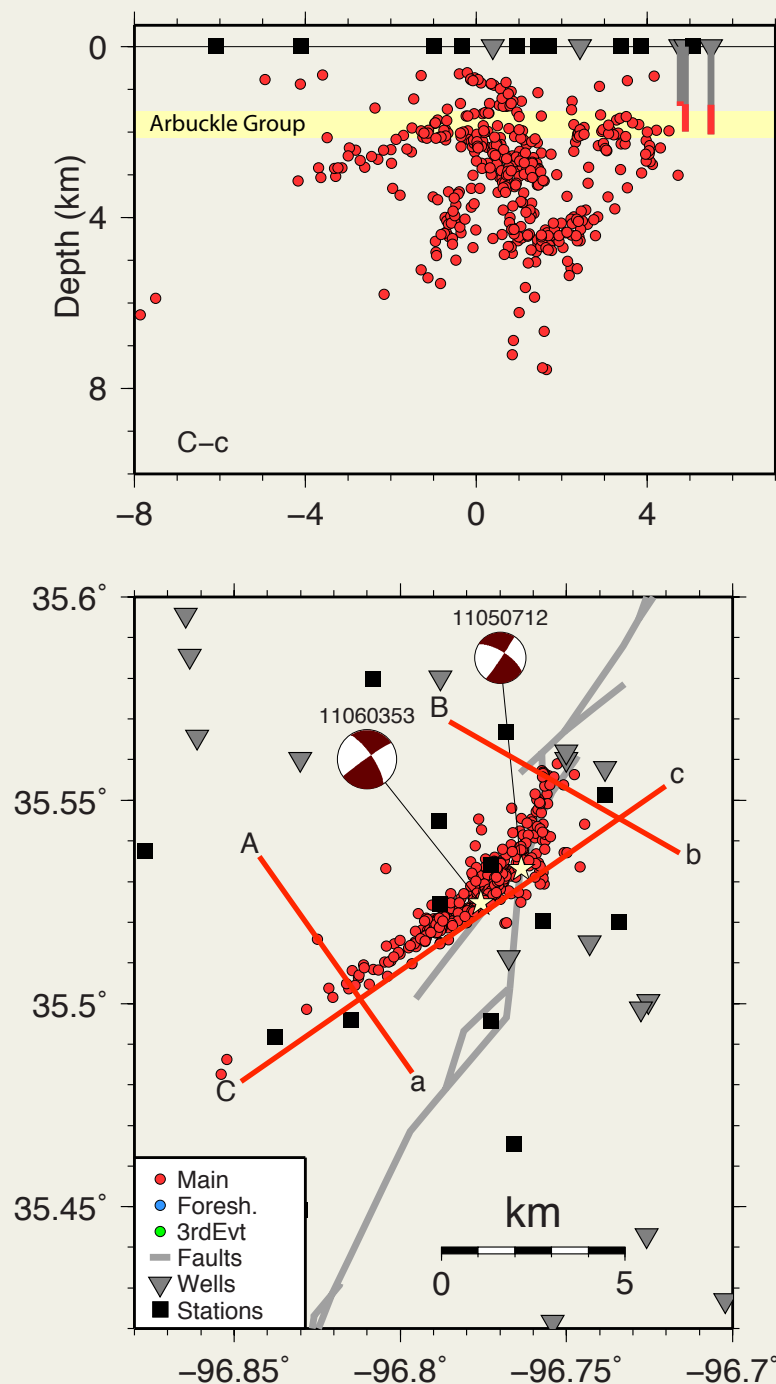
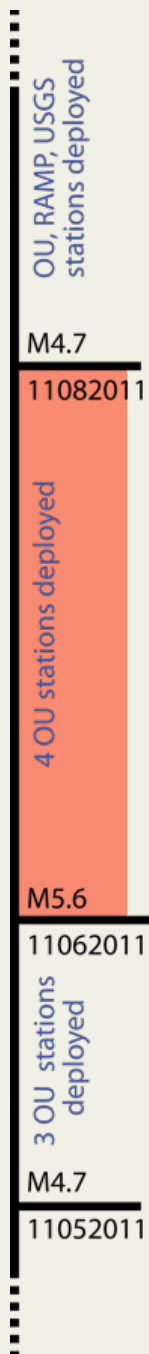
3 OU stations  
deployed

M4.7

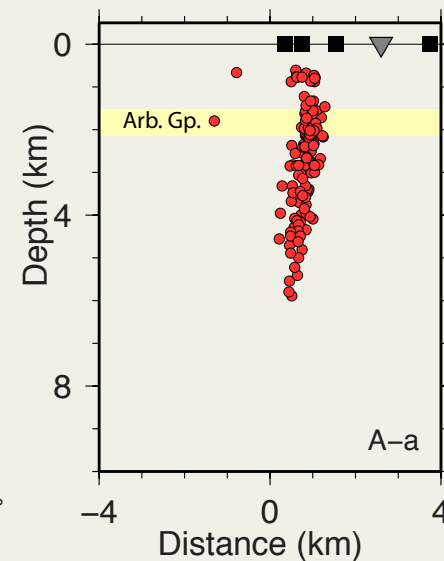
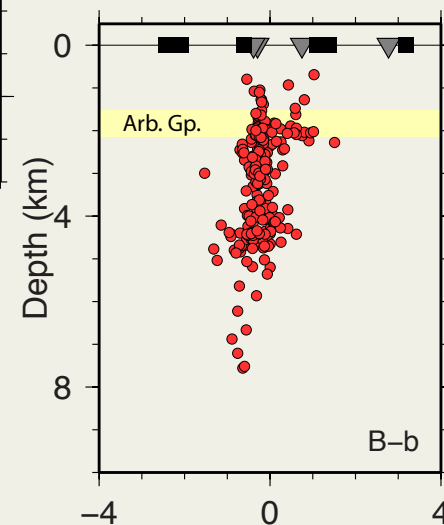
11052011



Timeline



Well path to maximum depth (zone of fluid injection in red)





Timeline

OU, RAMP, USGS  
stations deployed

M4.7

11082011

4 OU stations deployed

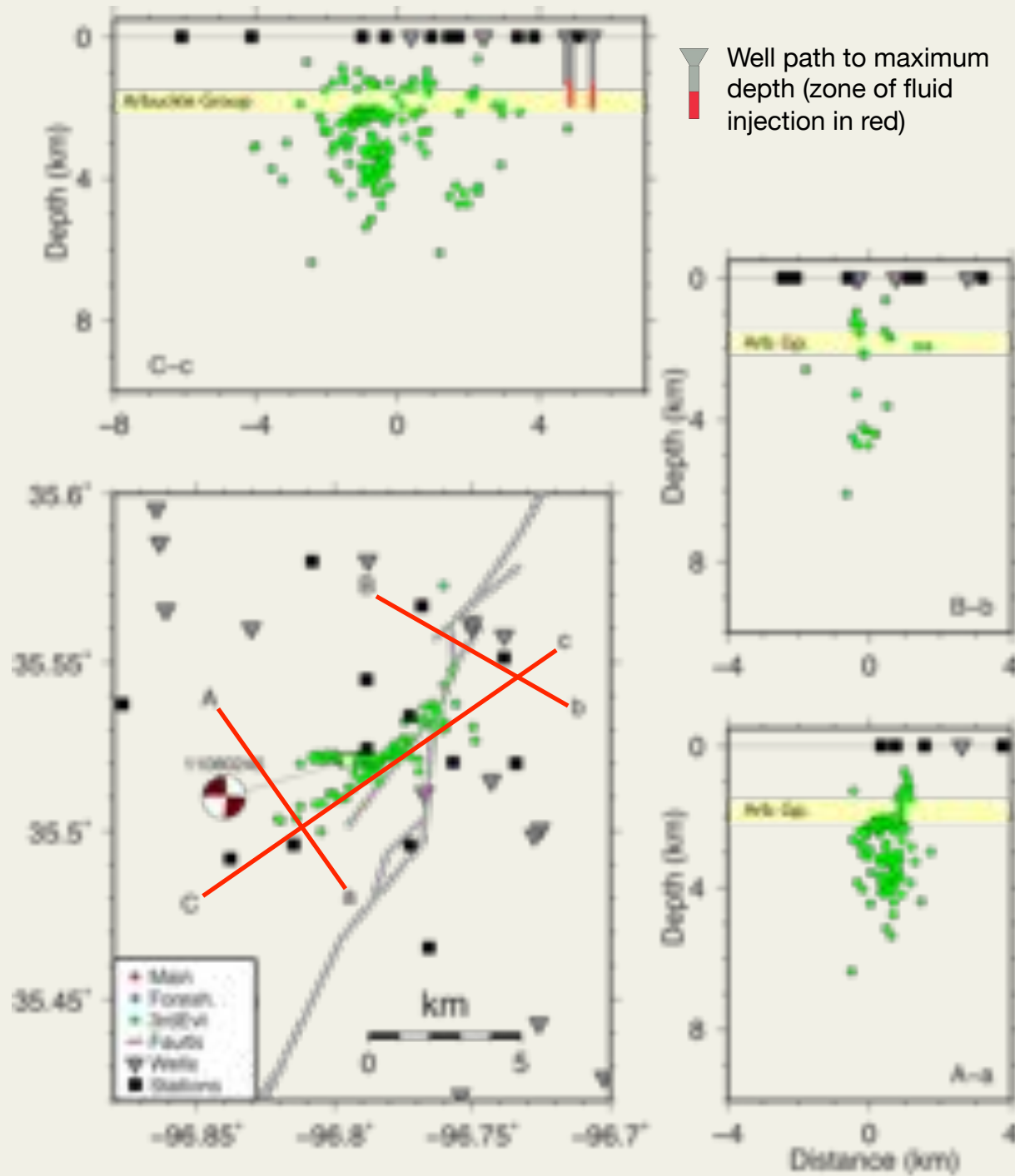
M5.6


11062011

3 OU stations  
deployed

M4.7

11052011



Timeline 

OU, RAMP, USGS  
stations deployed

M4.7

11082011

4 OU stations deployed

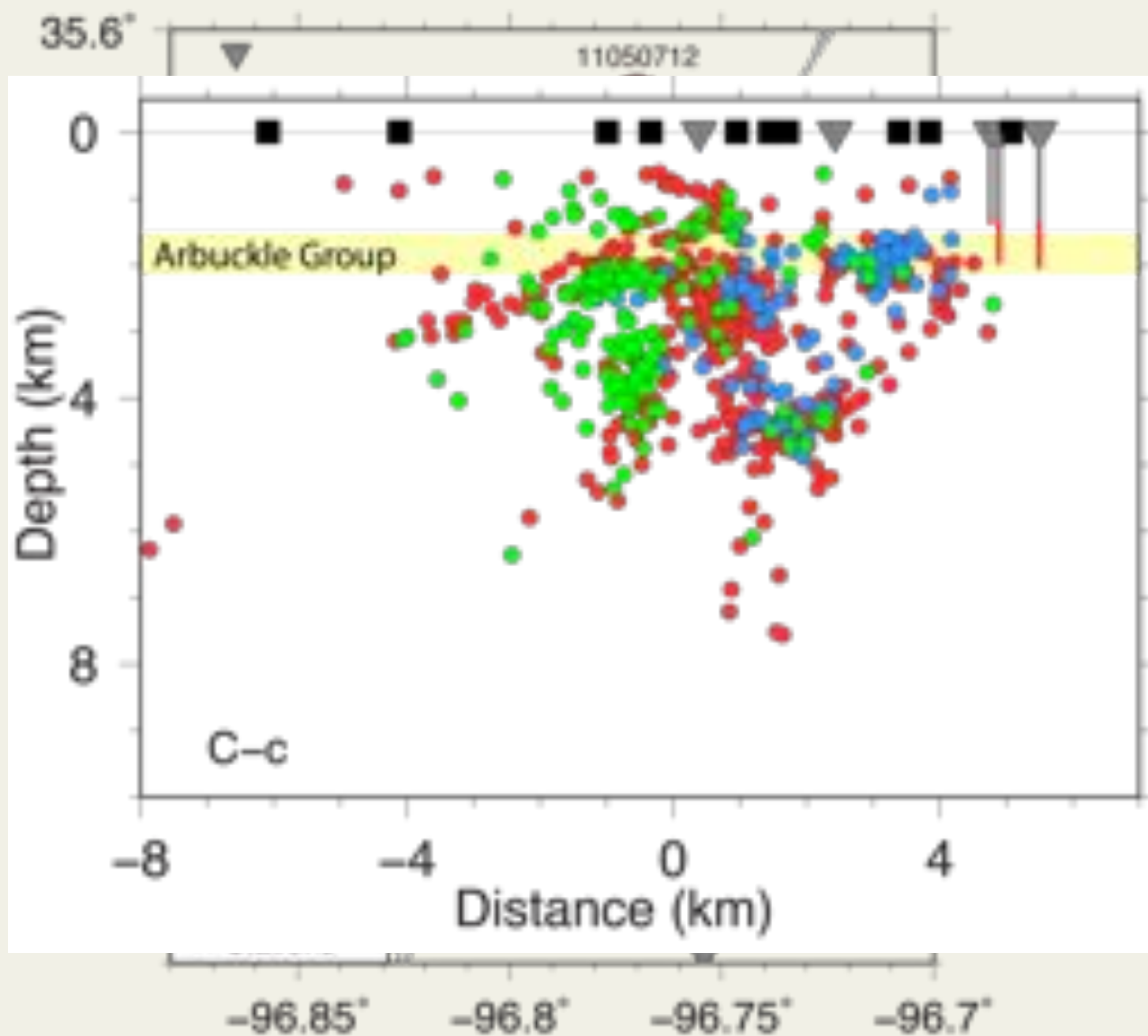
M5.6

11062011

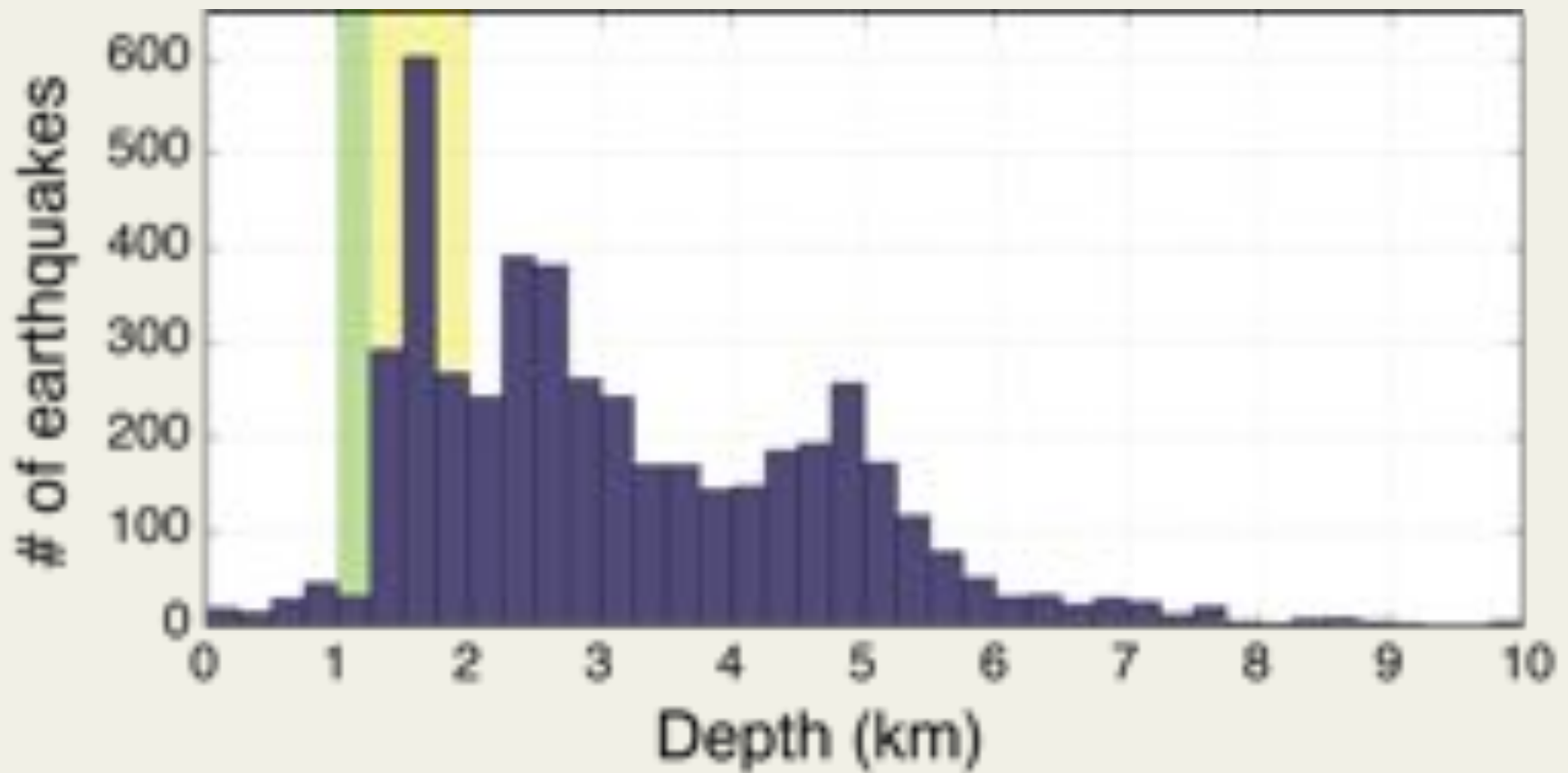
3 OU stations  
deployed

M4.7

11052011

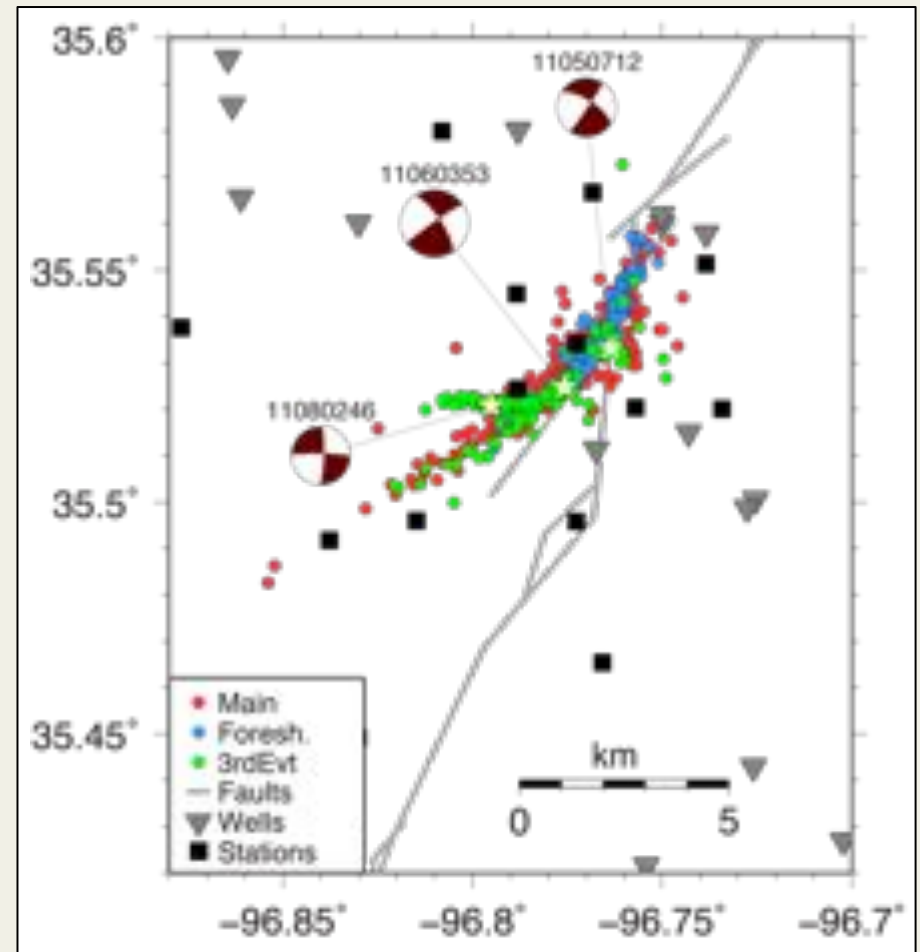


95% of hypocenters above 6 km  
30% of hypocenters in sedimentary units



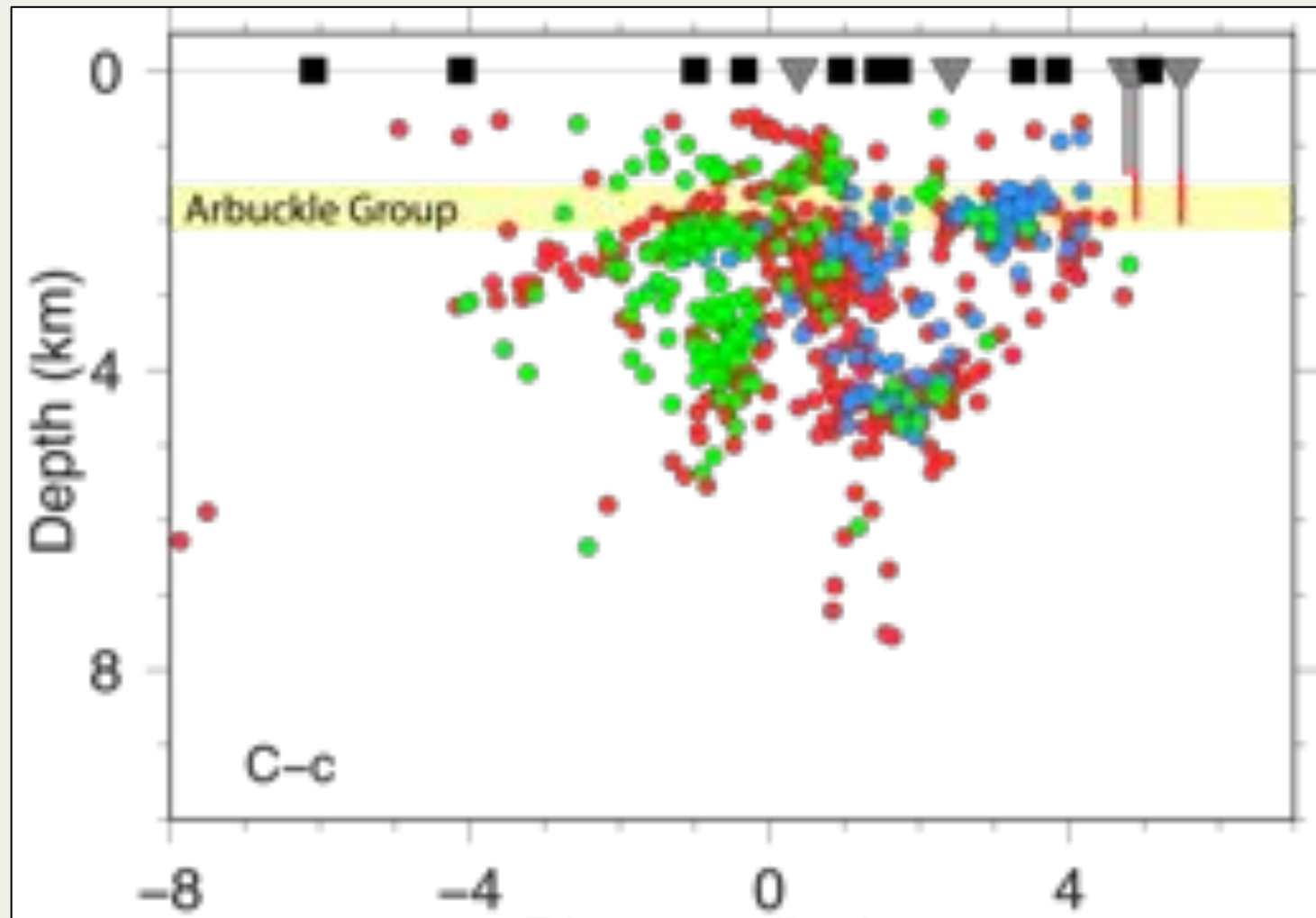
# Observations from the earthquake sequence

- Three narrow, near-vertical fault planes
- Northern tip of first event begins *at injection depths* within 100 meters of two injection wells
- Aftershocks from the first event propagate south and deepen away from the well





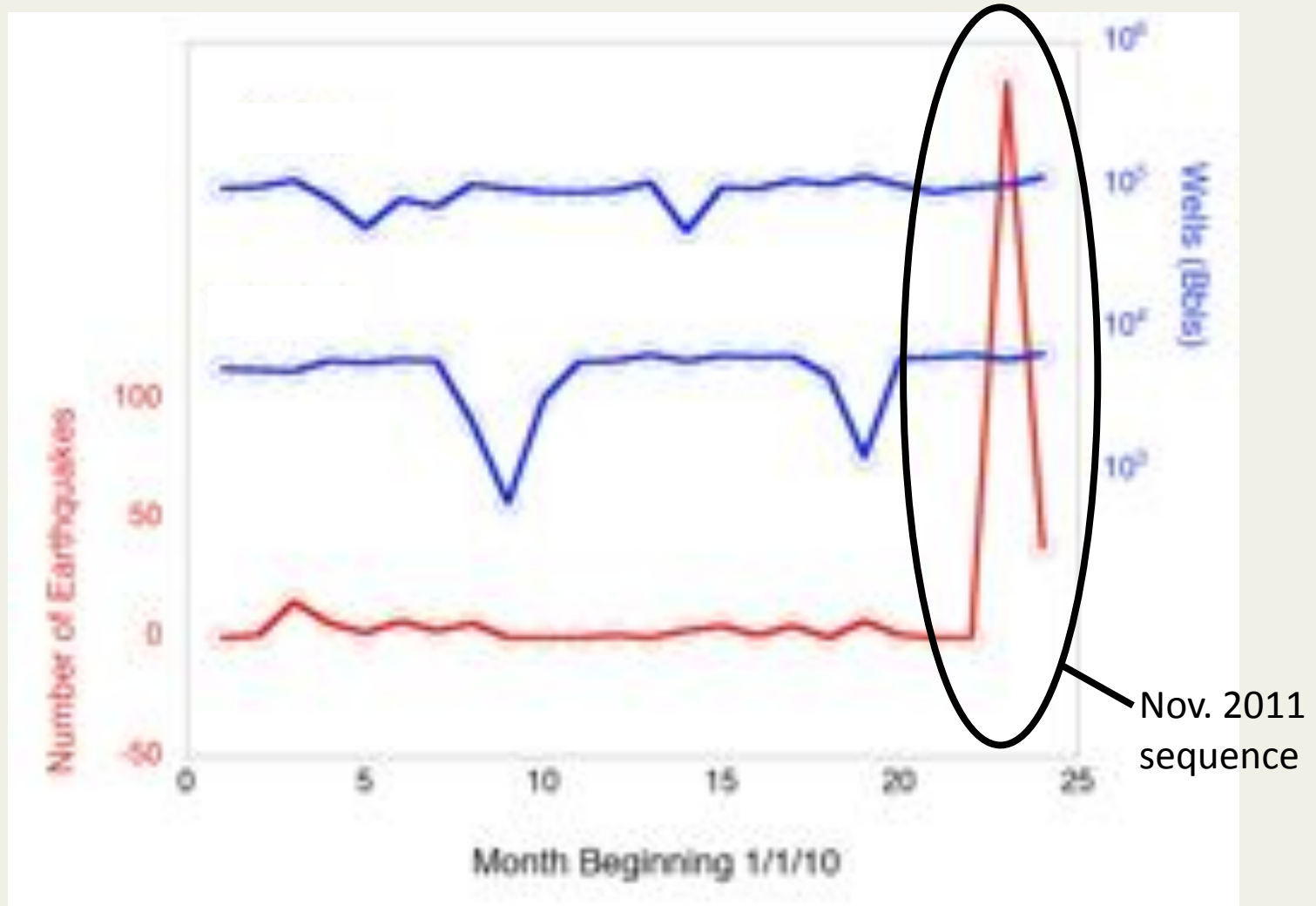
Fundamental observation: Compelling link between zone of injection and seismicity pattern



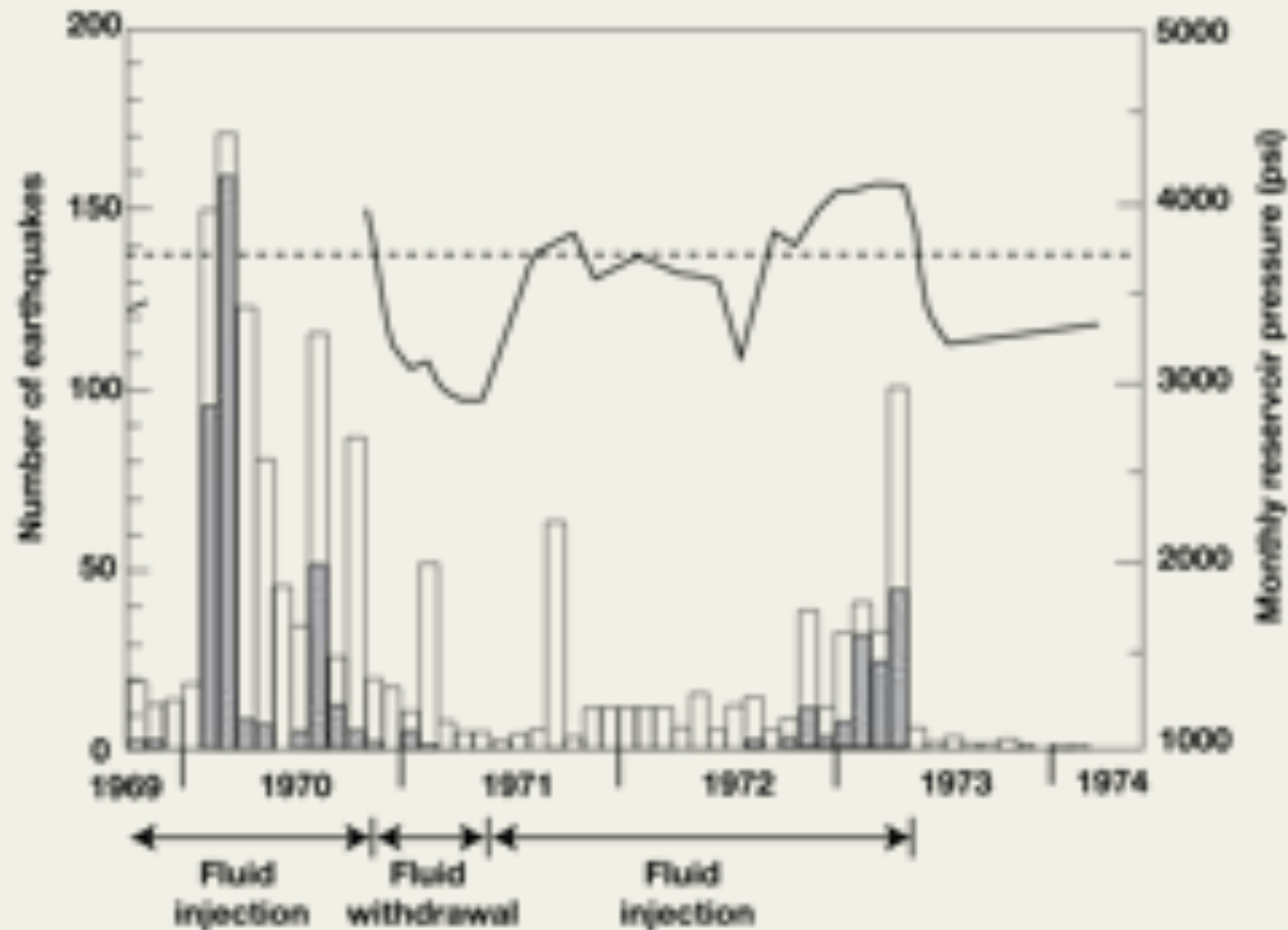
# Does this meet the criteria for induced seismicity?

- 1. Deviation from background seismicity ✓
  - 2. Spatial correlation of seismicity with injection wells ✓
  - 3. Seismicity within the depth intervals of fluid injection ✓
- 
- 4. Temporal correlation to injection practices (injection pressure, injection rate) ?
  - 5. Increased fluid pressure in the subsurface beyond a critical threshold

Is there a temporal relationship observed between fluid injection (pressure, rate) and seismicity rate near Prague?

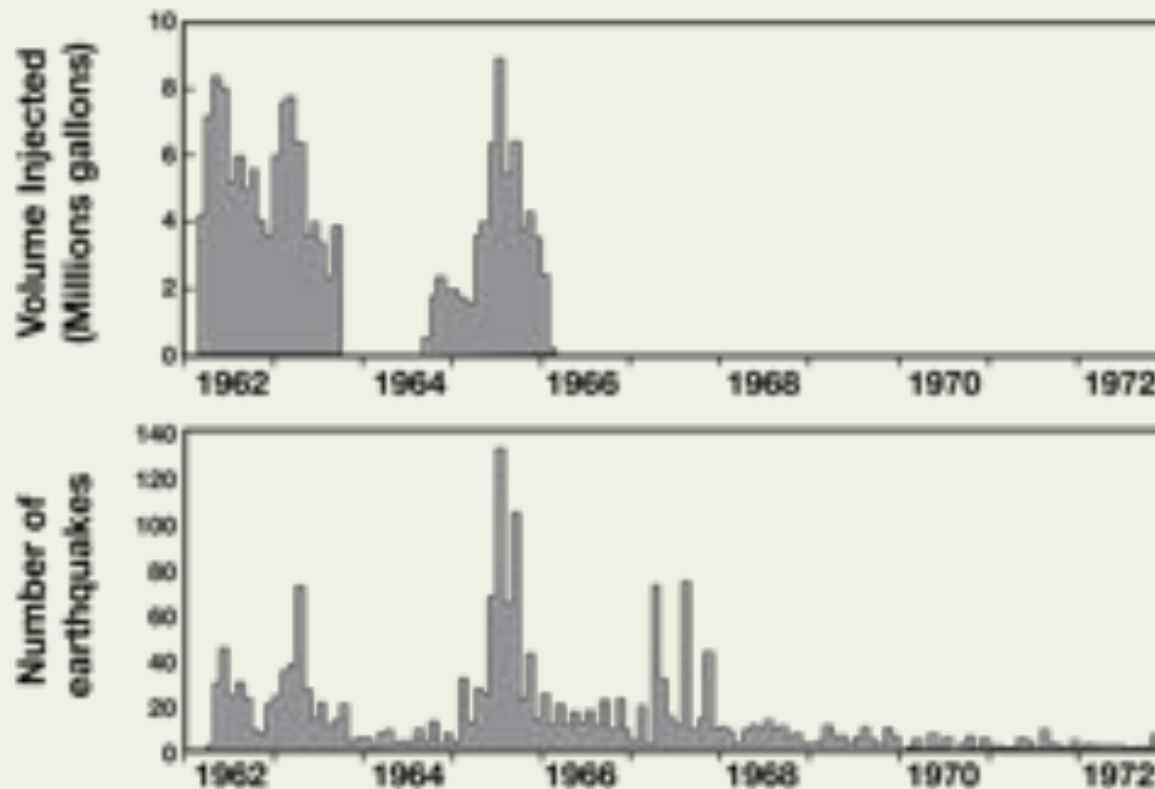


# Seismicity spiked at Rangely when pressure surpassed critical threshold

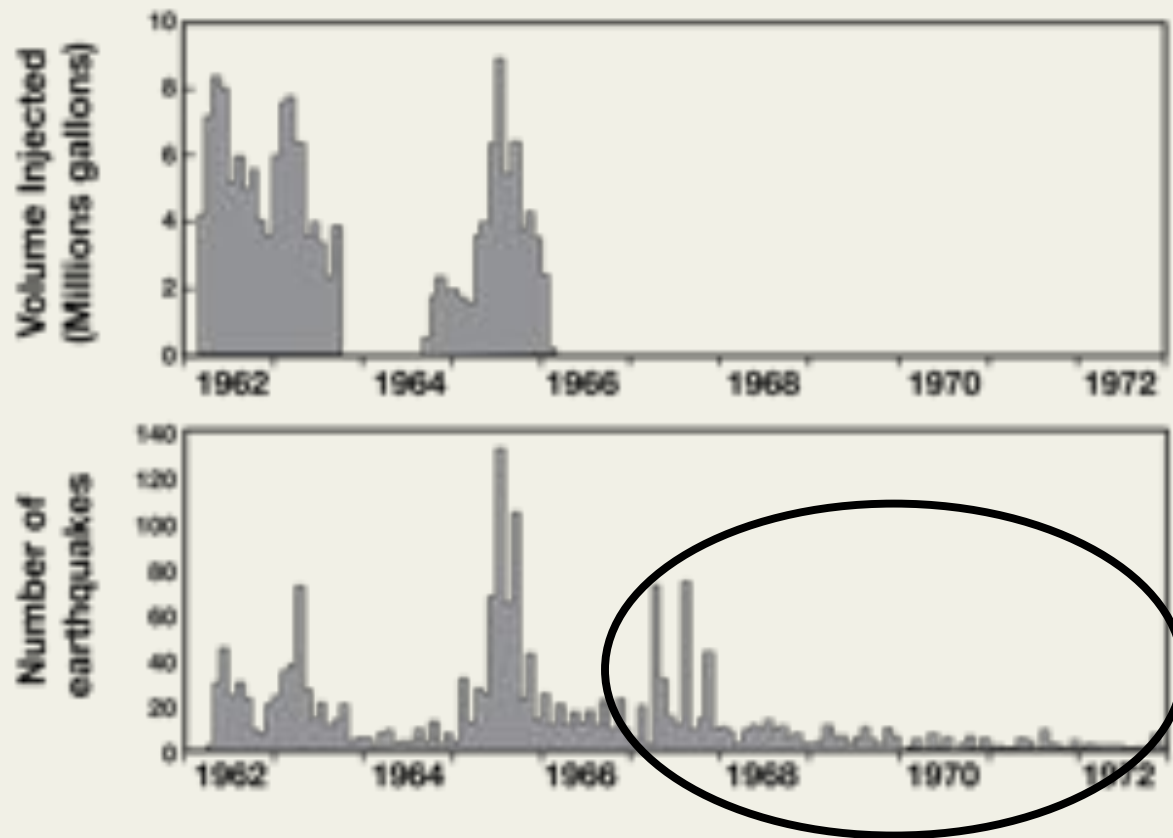




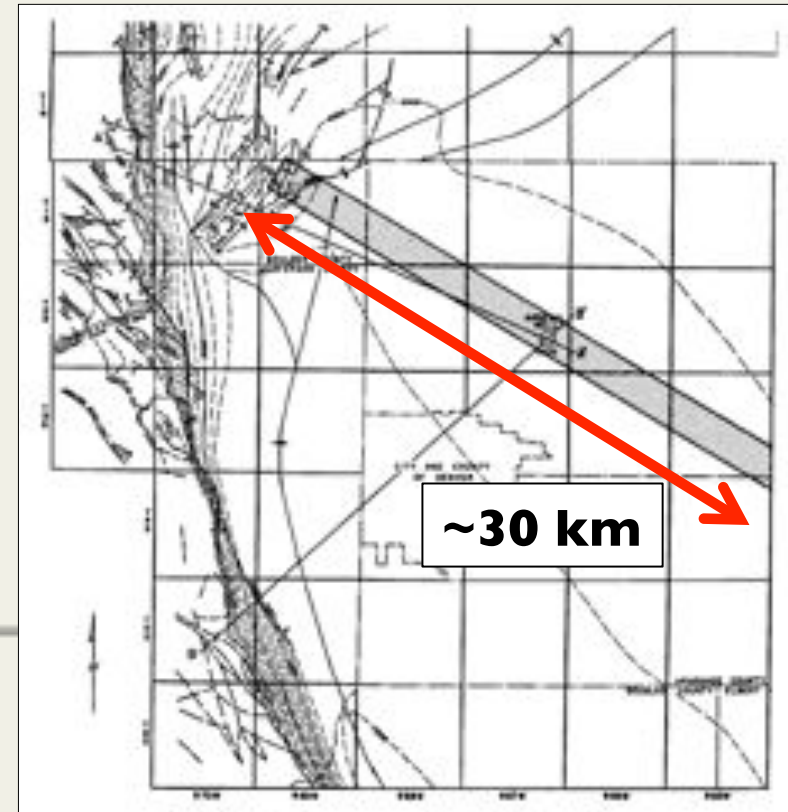
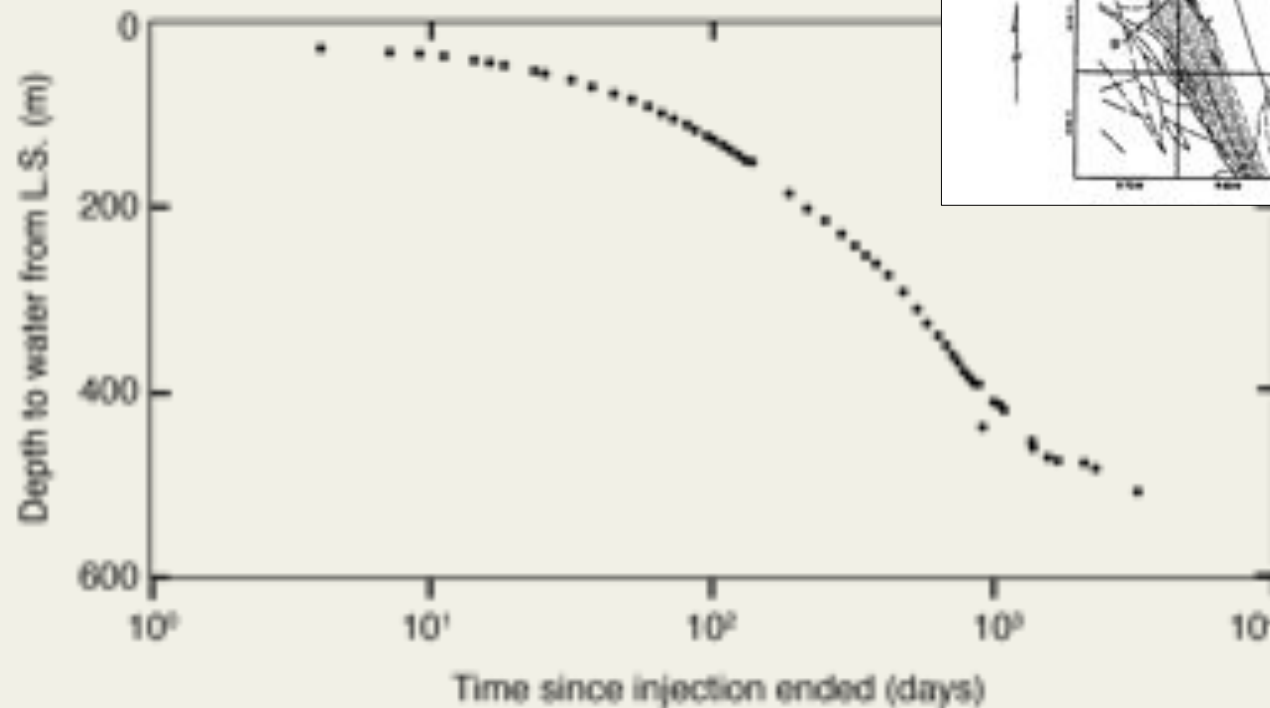
# Seismicity in phase with injected volume at the Rocky Mountain Arsenal



# Seismicity continued for years following the end of injection at the RMA

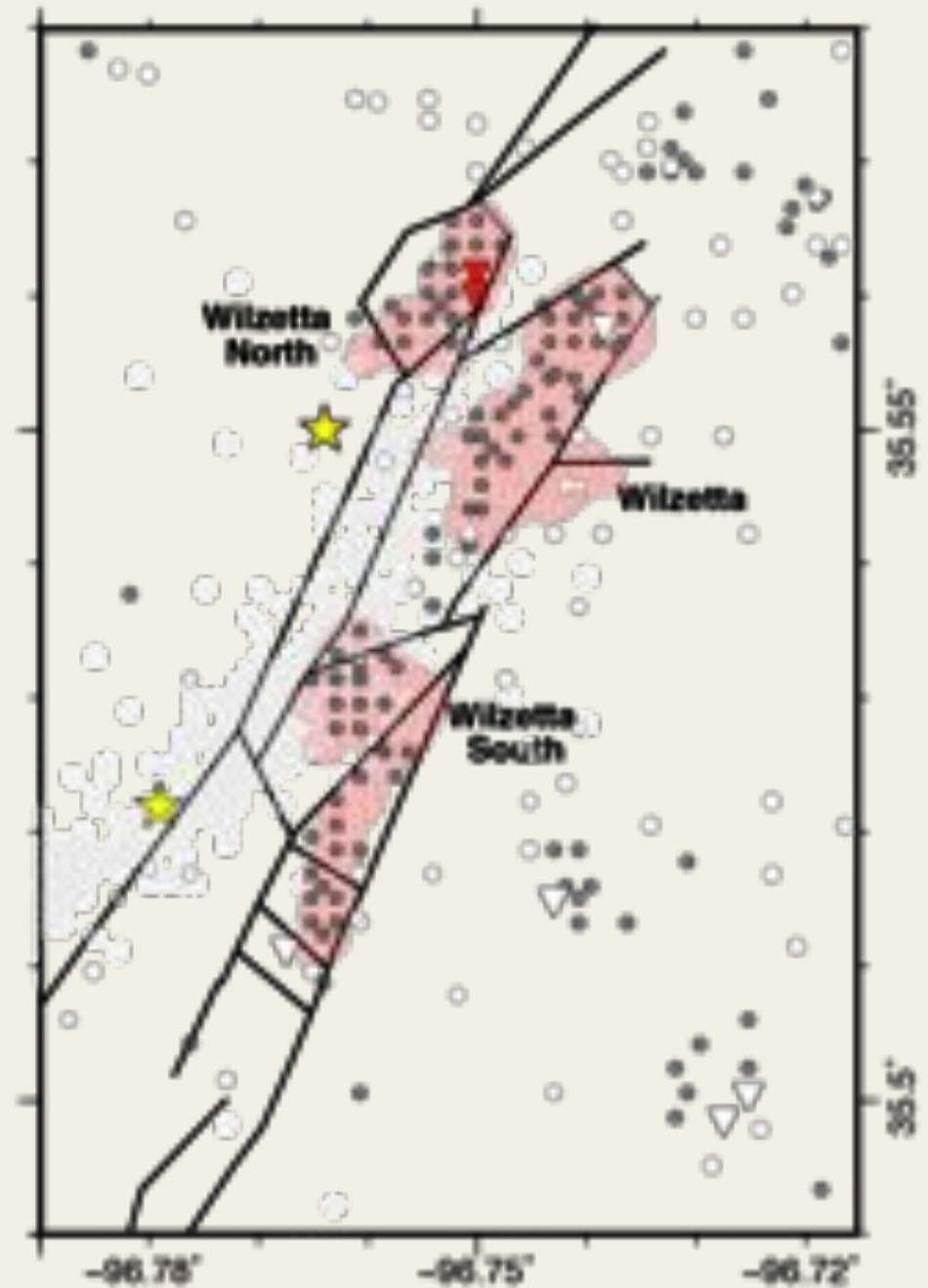


# Effects of lateral boundaries on fluid pressure

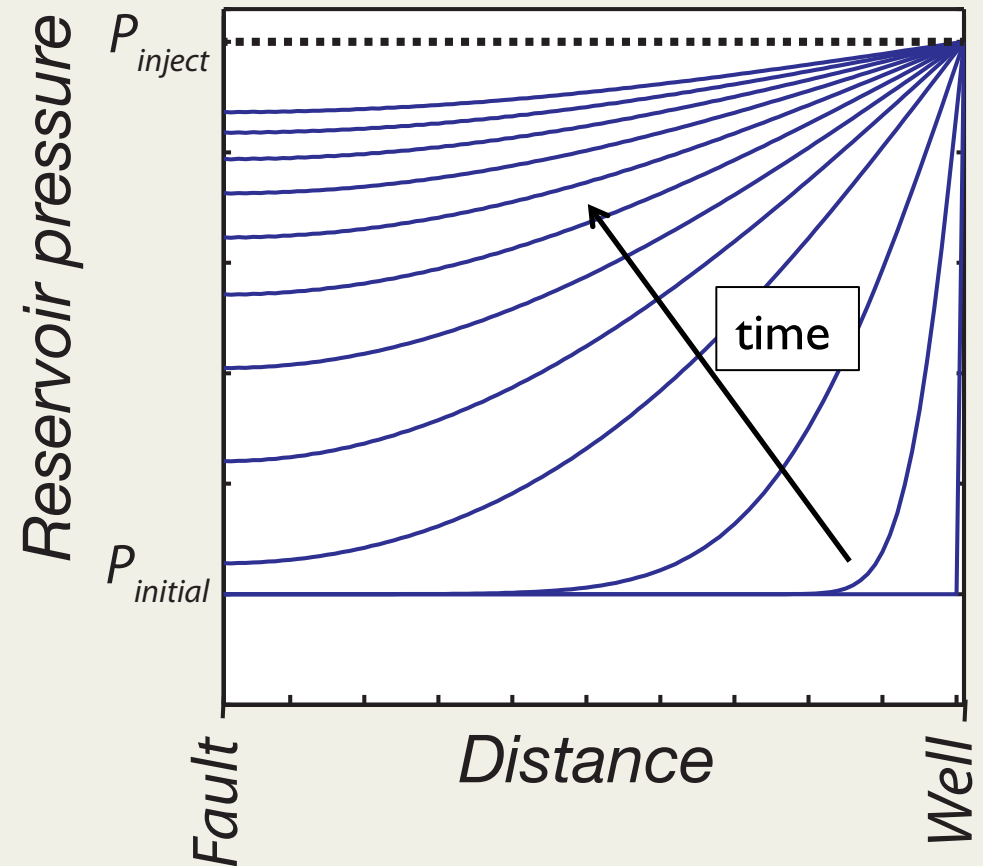
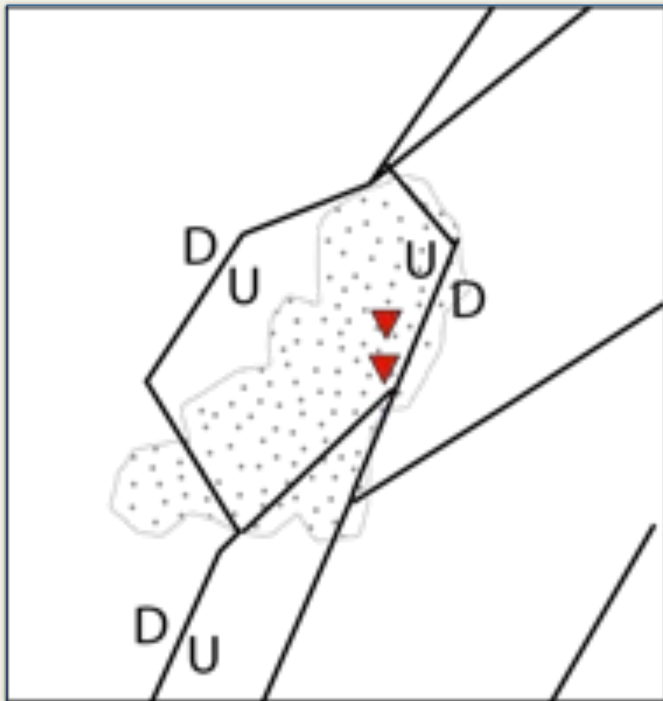


Faults create  
reservoir  
compartments

There appears to  
be limited fluid  
communication  
across faults

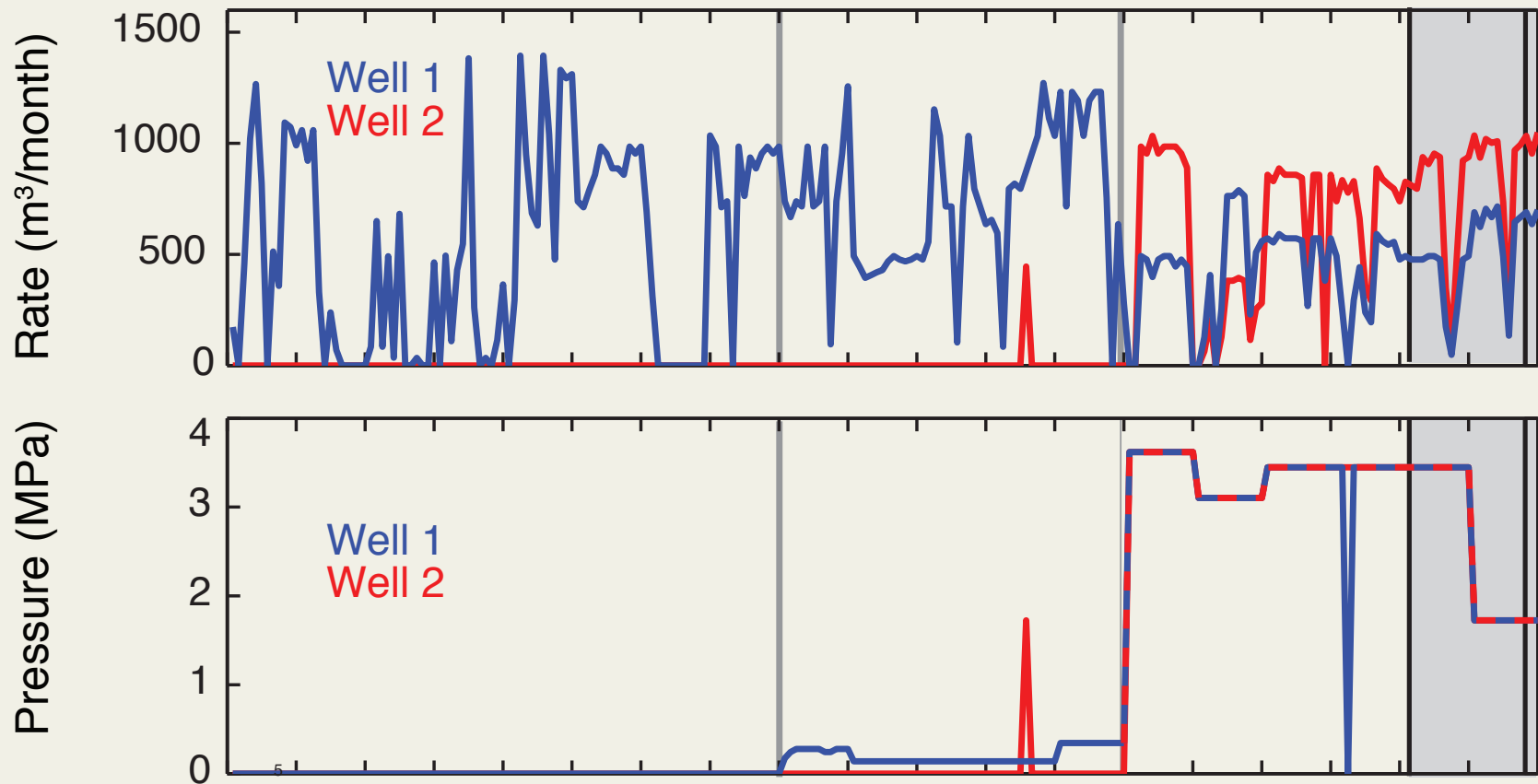


# Effects of lateral boundaries on reservoir pressure

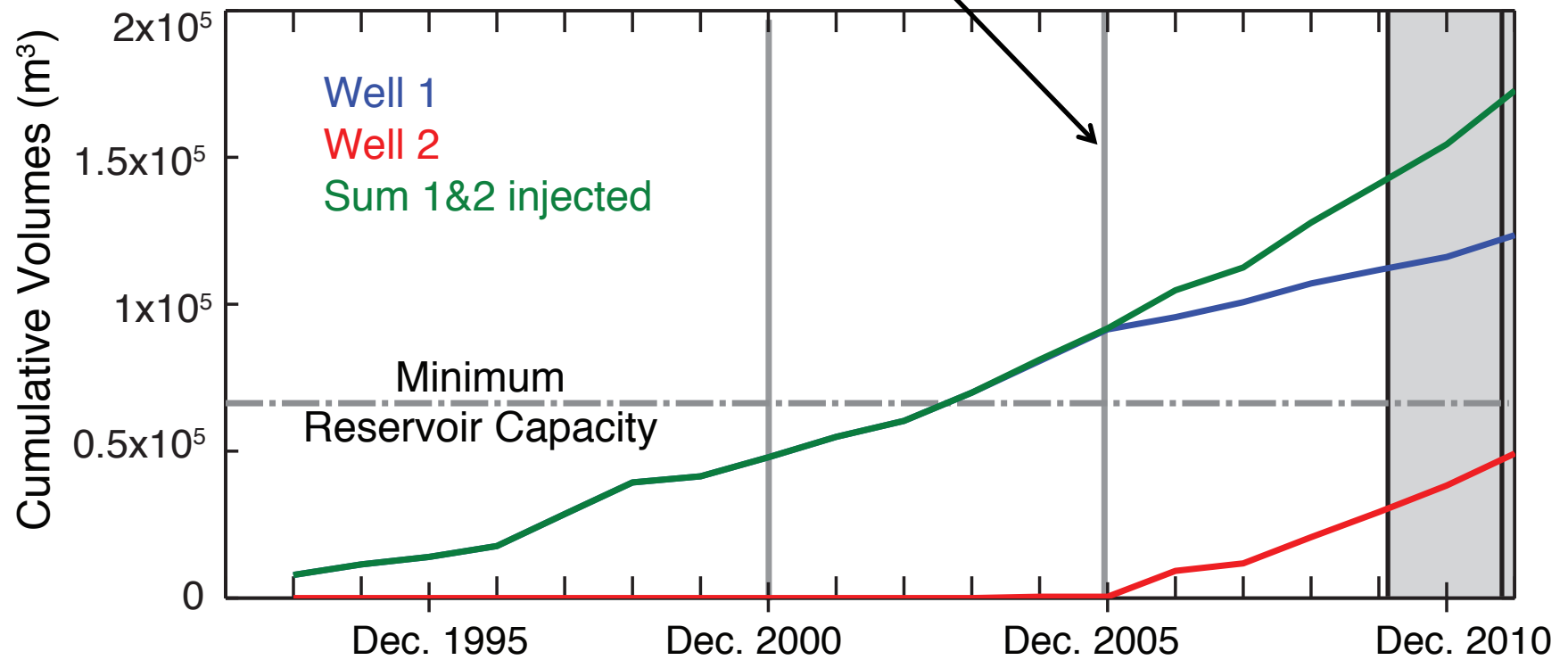




Volume roughly constant on a monthly basis  
Pressure was increased in steps

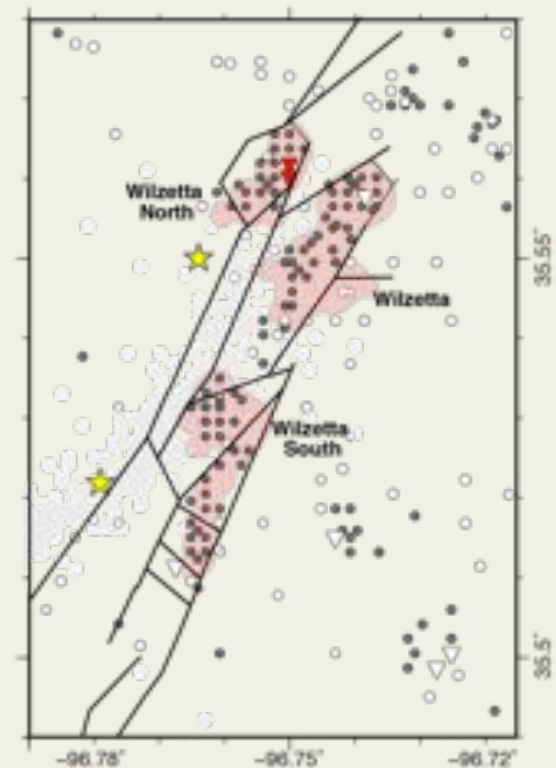
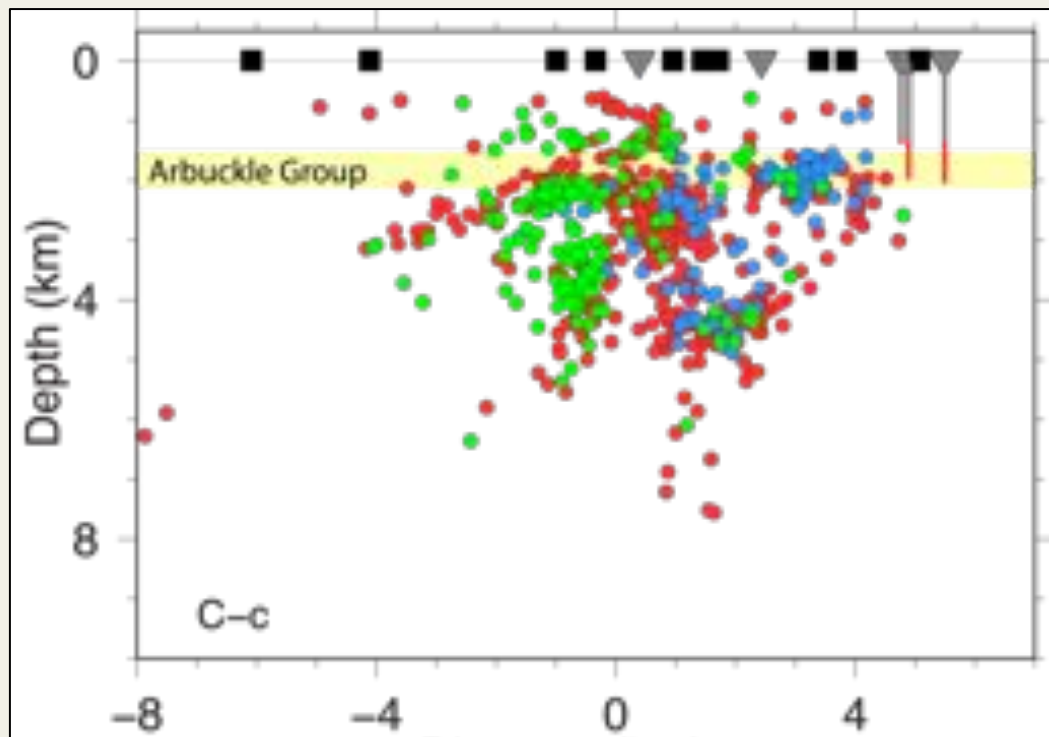


Large pressure increase



# Summary of earthquake sequence

1. Compelling link between zone of injection and seismicity pattern
2. Injection occurs into small faulted compartments



# Broader implications

- Oklahoma sequence suggests that a long temporal delay (10-20 years) is possible
  - Permeability barriers can delay pressure relaxation; cause a gradual increase in pore pressure
- We do not always expect a correlation between short-term fluctuations in wellhead injection data and seismicity
- Significant tectonic stress released
  - The volume of fluid injected near Prague is orders of magnitude below that predicted for the M5.0 event



# What about the criteria for induced seismicity?

1. Deviation from background seismicity
2. Spatial correlation of seismicity with injection wells
3. Seismicity within the depth intervals of fluid injection
4. ~~Temporal correlation to injection practices~~ ?  
(~~injection pressure, injection rate~~)
5. **Increased fluid pressure in the subsurface beyond a critical threshold**



# ACKNOWLEDGEMENTS

Caitlin Dieck (LDEO), Khanh Pham (OU), and Gabriel Mattei (OU)  
Danielle Sumy (USGS-Pasadena)

Special thanks to all those who helped with field deployment (OU, OGS, OSU, USGS) and the PASSCAL staff for RAMP equipment and frequent discussion

The Oklahoma Corporation Commission, for well data and discussions  
Discussion with many individuals including Bill Ellsworth, Steve Hickman, Emily Brodsky, Wayne Pennington, Chris Scholz, Mark Zoback, Austin Holland

OU School of Geology and Geophysics for financial support

# THANK YOU

Friday sessions with further posters and talks on the Oklahoma sequence:

S51E/S53I/S54D: Understanding Recent and Historical Seismicity in the Central and Eastern U.S. I & II

*Conveners: W. Ellsworth and G.R. Keller*

S52D-01. P and S Travel Time Tomography Using a Dense Array of Portable Seismographs and Earthquake Sources in Central Oklahoma

*Authors: C. Toth, A. Holland, G. R. Keller, and S. Holloway*

